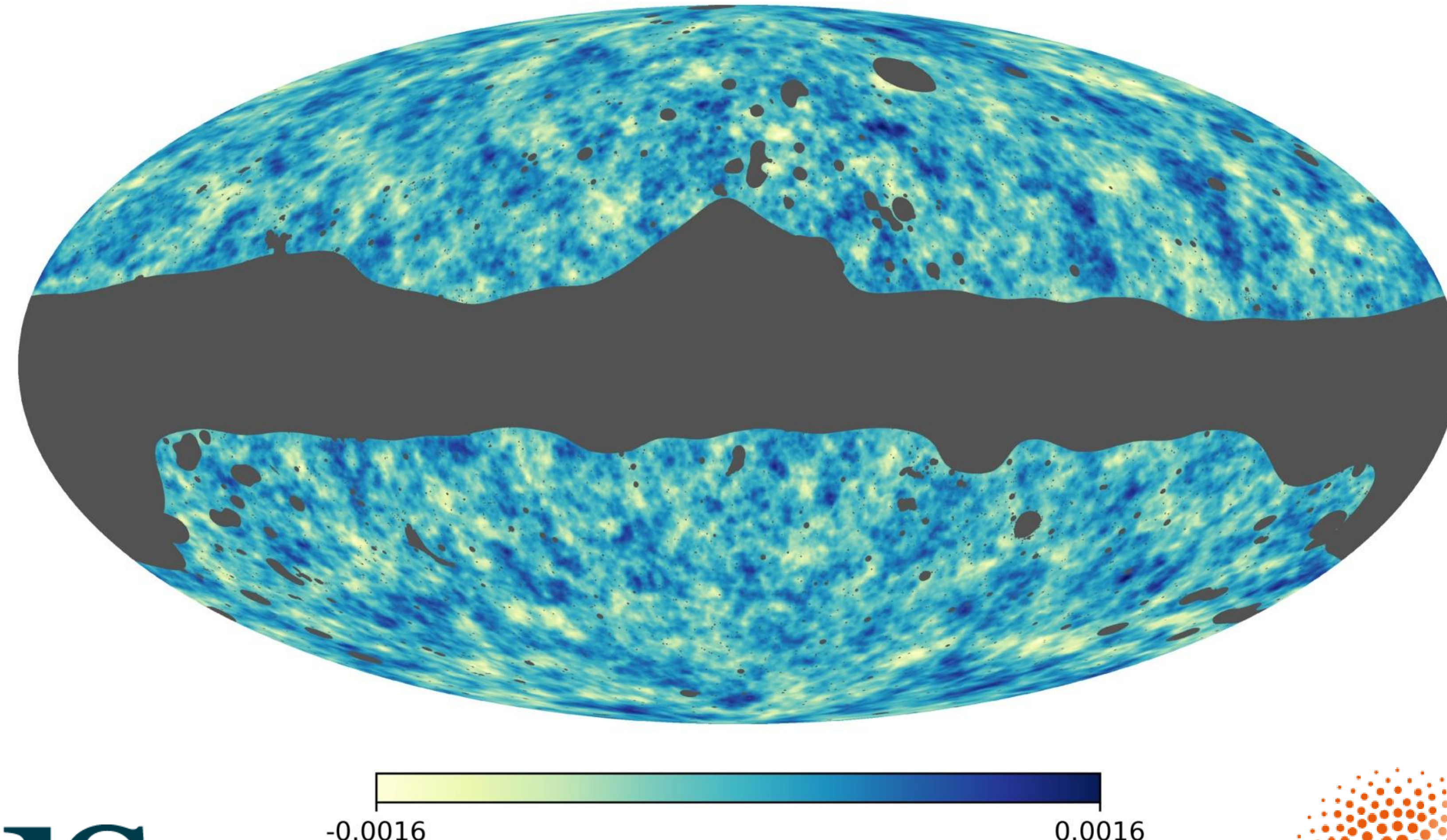
CMB Lensing and Delensing



Antony Lewis

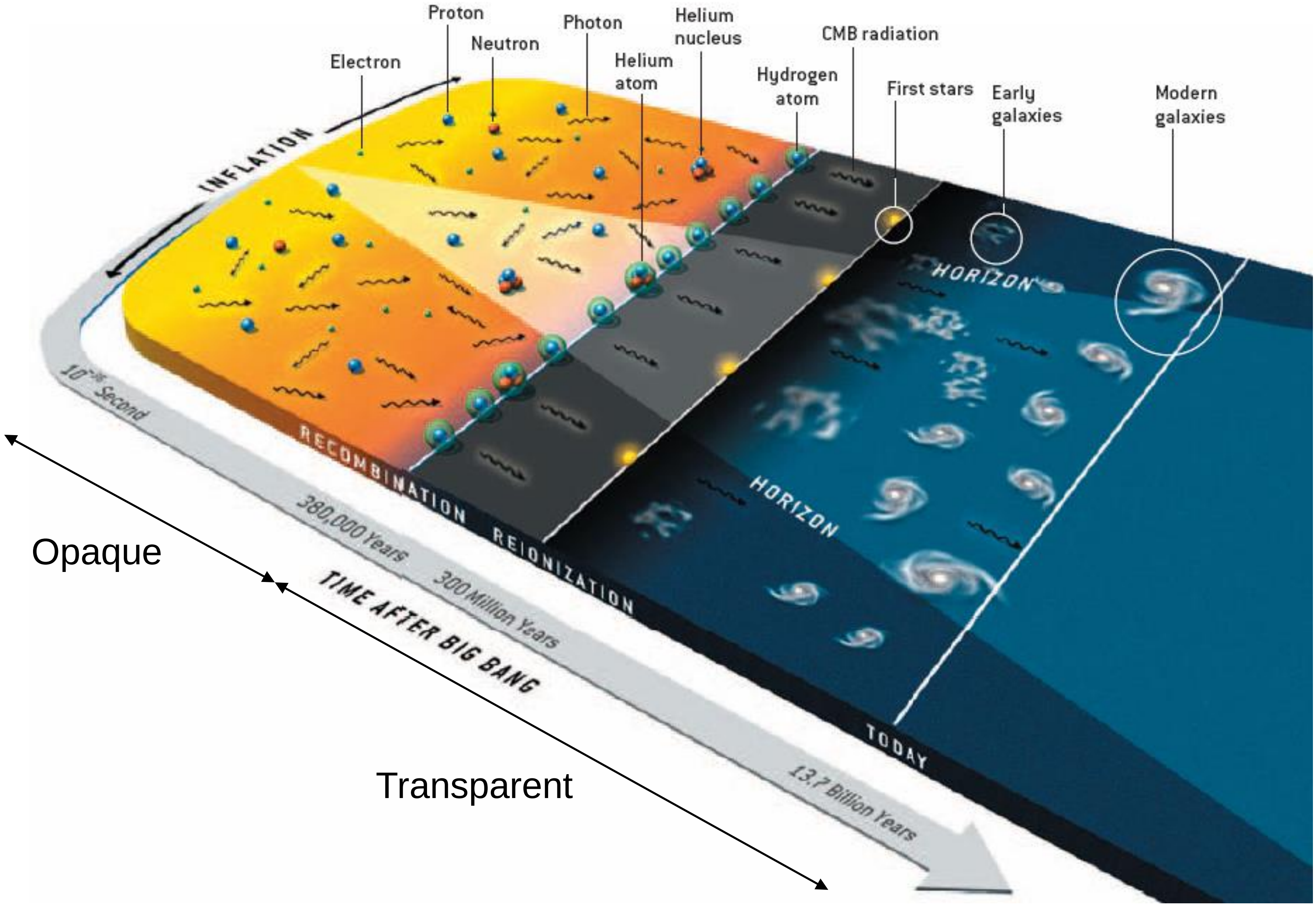
http://cosmologist.info/

UNIVERSITY OF SUSSEX

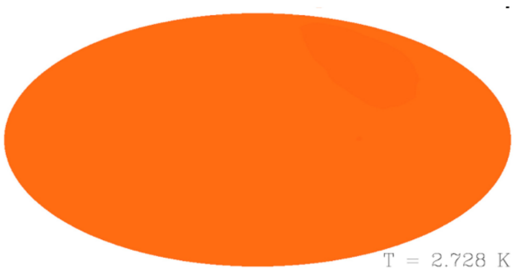
European Research Council

Established by the European Commission

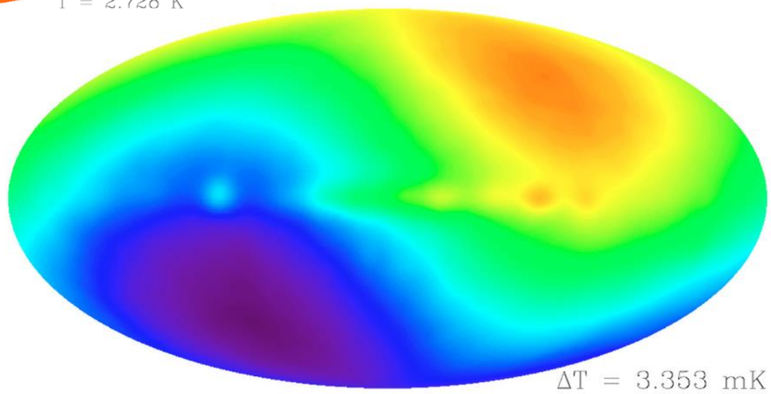
Evolution of the universe



Hu & White, Sci. Am., 290 44 (2004)

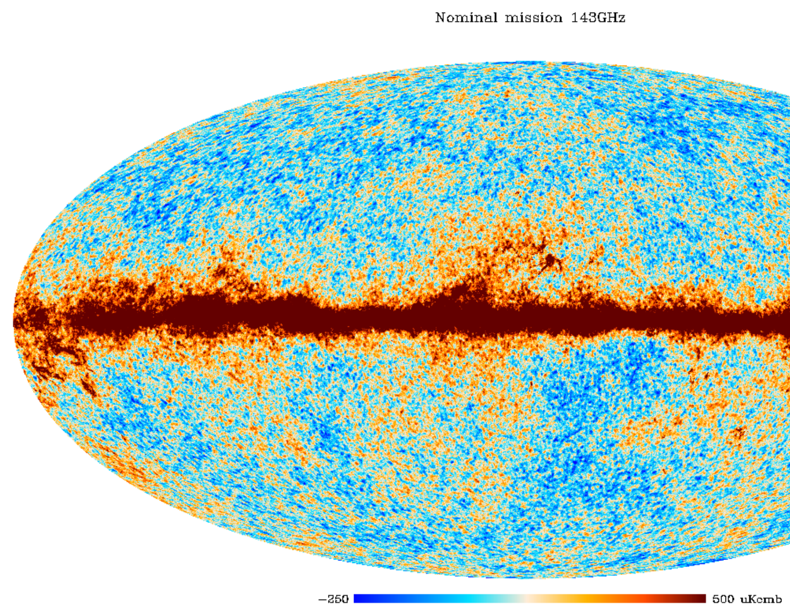


(almost) uniform 2.726K blackbody

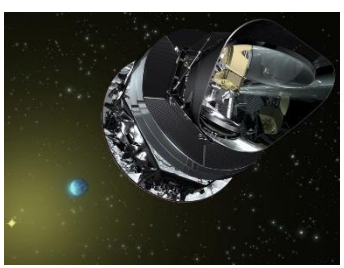


Dipole (local motion)

$O(10^{-5})$ perturbations (+galaxy)



Observations:
the microwave sky today

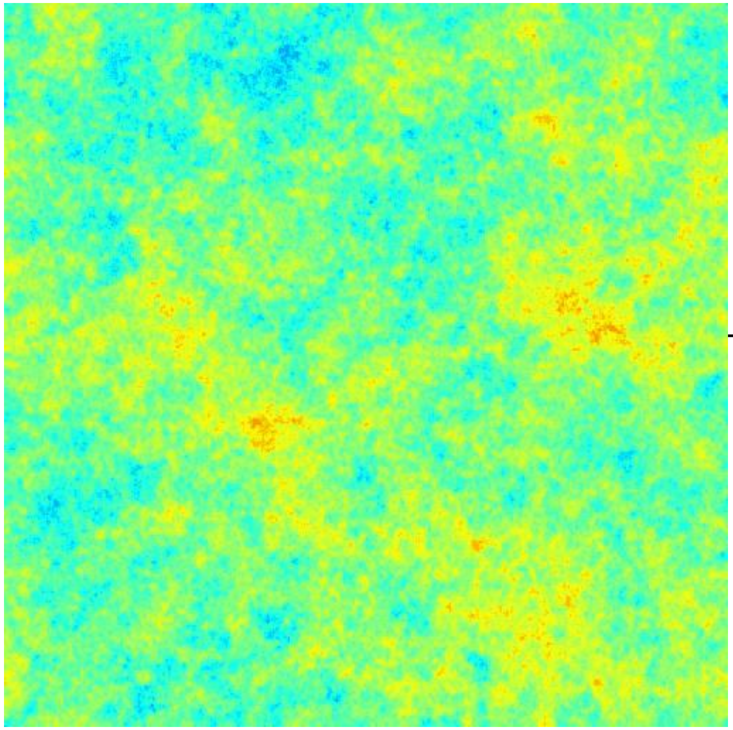


Planck Satellite

0^{th} order (uniform 2.726K) + 1^{st} order perturbations (anisotropies)

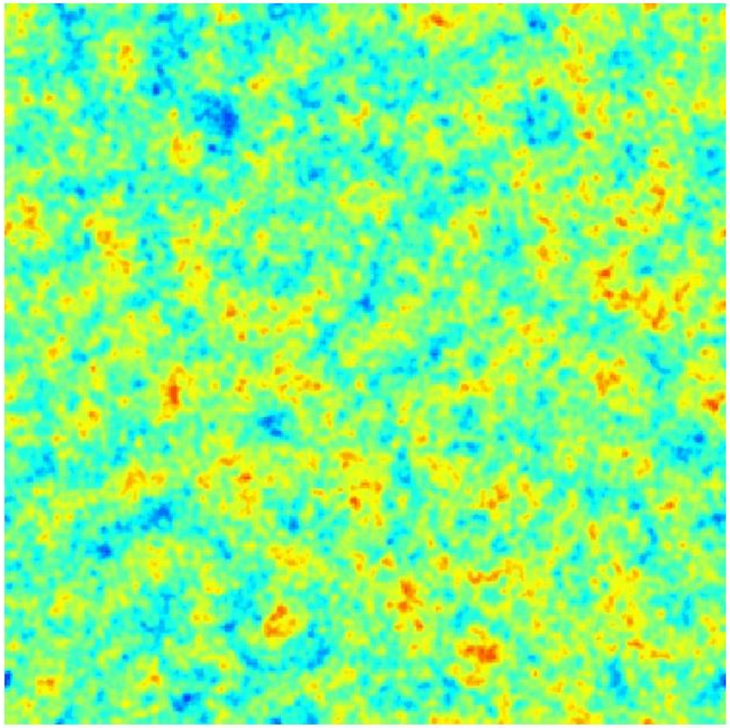
Perturbation evolution

Perturbations: End of inflation

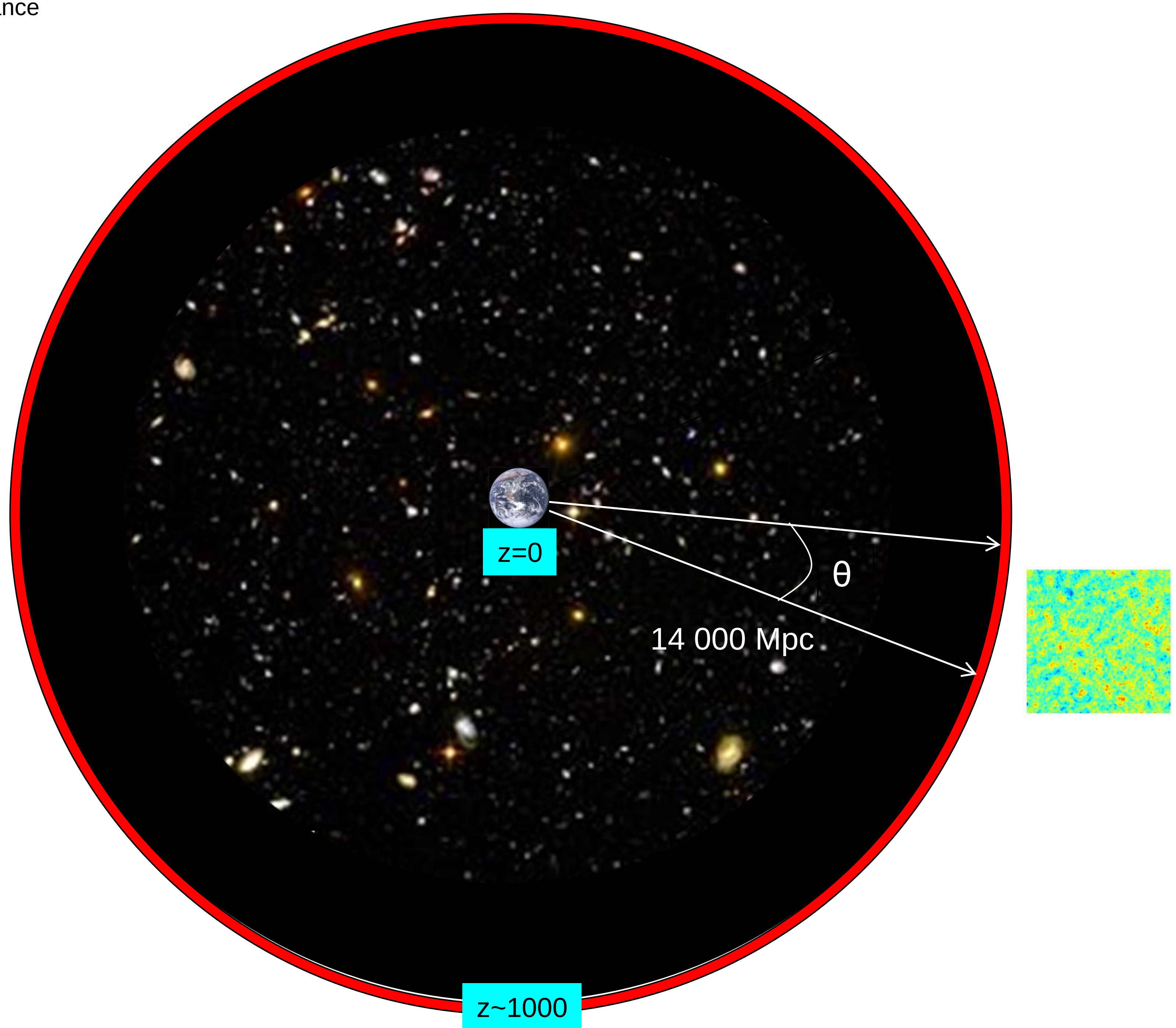


gravity+
pressure+
diffusion

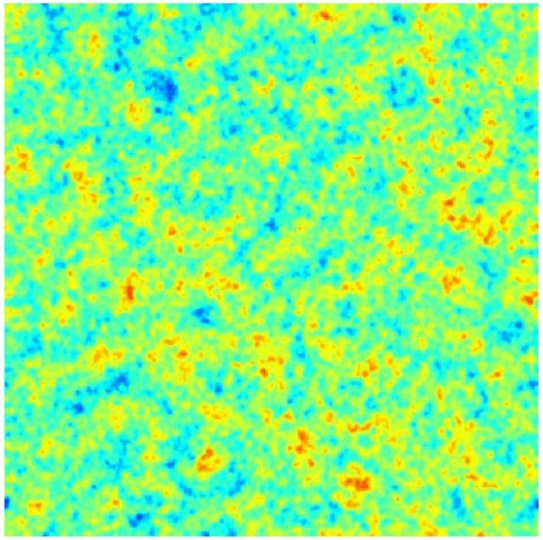
Perturbations: Last scattering surface



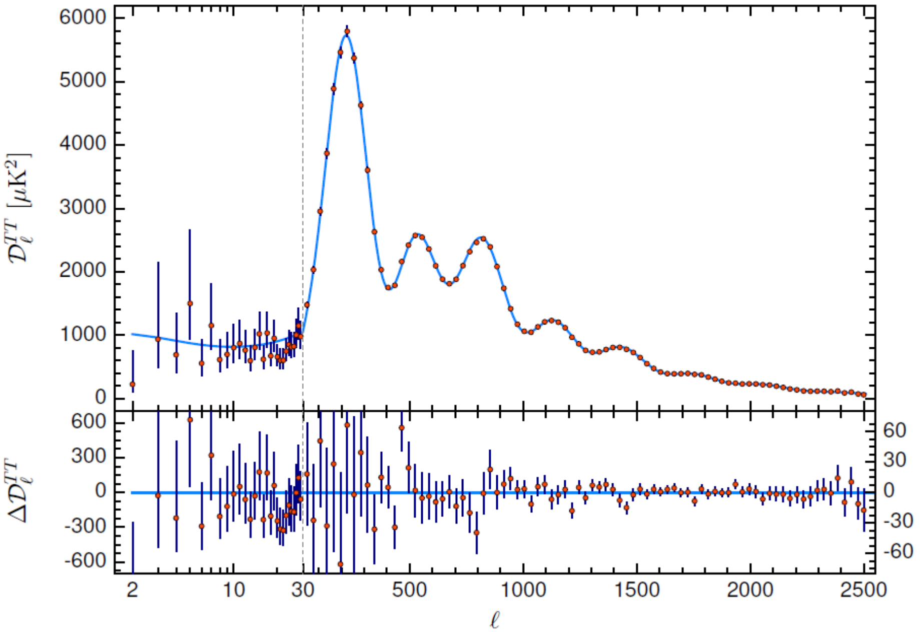
In comoving distance



Observed CMB power spectrum



Planck 2018 arXiv:1807.06209



Observations

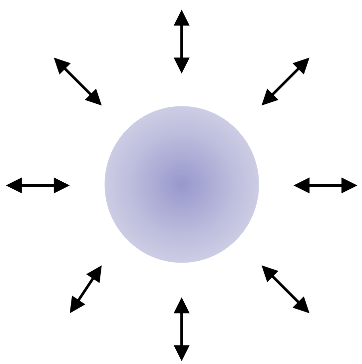
Constrain theory of early universe
+ evolution parameters and geometry

E and B polarization

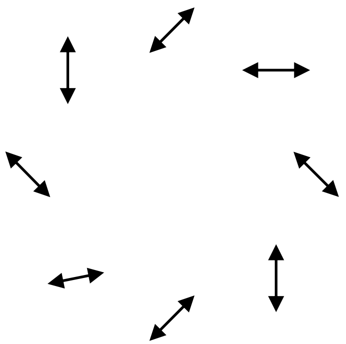
Trace free gradient:
E polarization

Curl:
B polarization

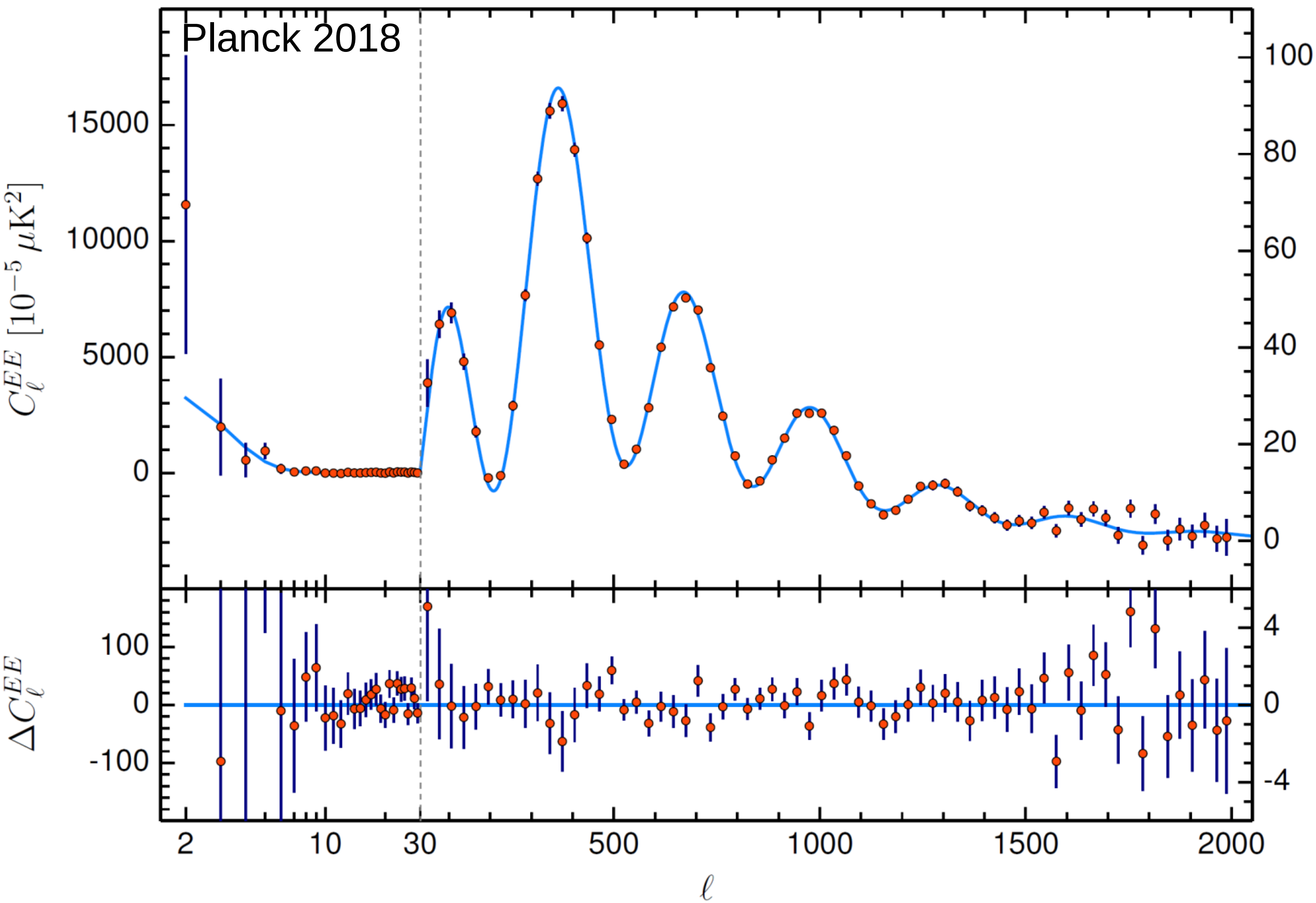
e.g.



e.g. cold spot

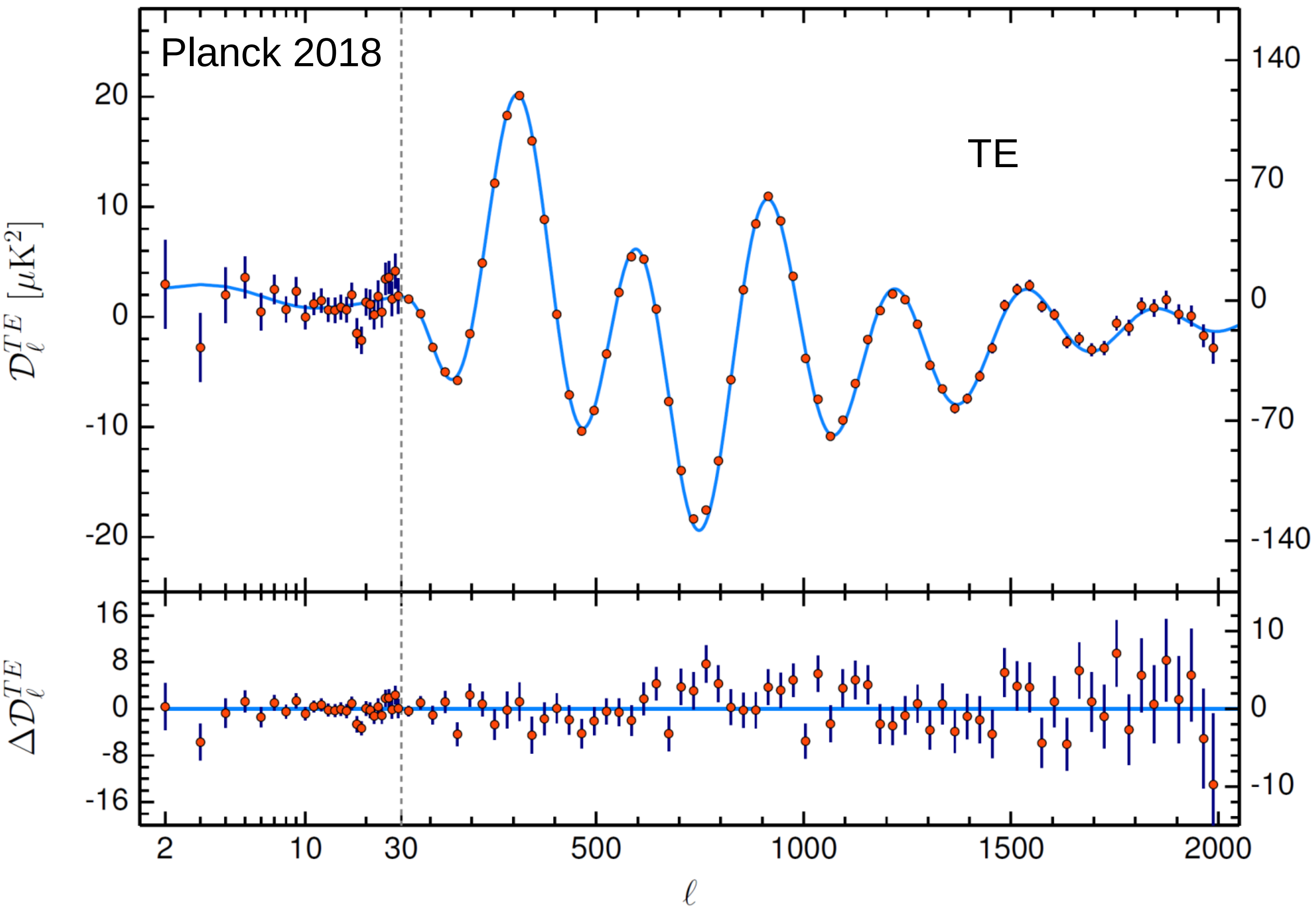


E-mode polarization

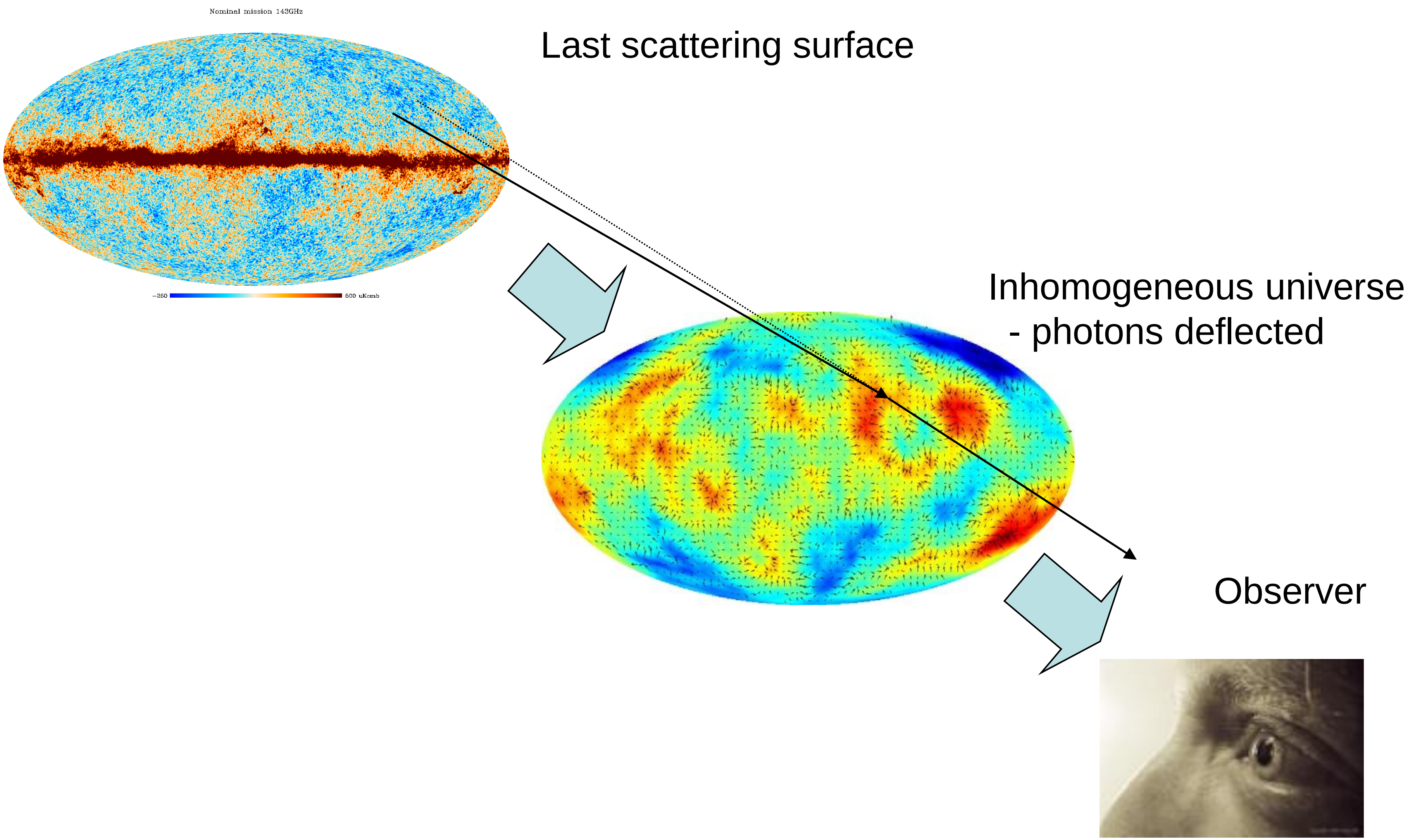


+ ACT/SPT/ACTpol/SPTpol ground-based in progress
Forthcoming ground-based: Simons Observatory, S4

and cross-correlation with temperature



Weak lensing of the CMB perturbations

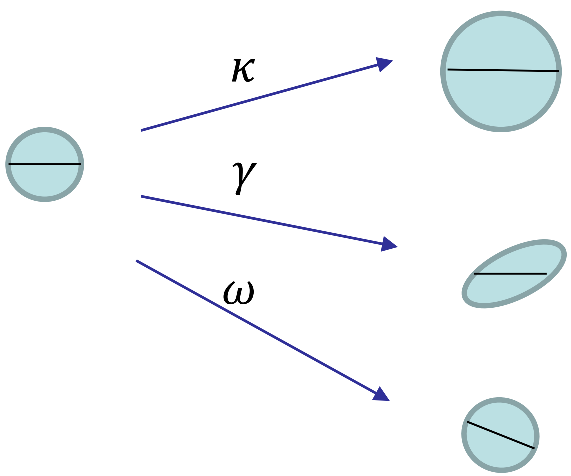


Lens remapping approximation: deflection angle $\boldsymbol{\alpha}$

$$X^{\rm len}(\boldsymbol{n}) = X^{\rm unl}(\boldsymbol{n} + \boldsymbol{\alpha}(\boldsymbol{n}))$$

Deflection related to shear γ_i , convergence κ , and rotation ω

$$A_{ij} \equiv \delta_{ij} + \frac{\partial}{\partial \theta_i}\alpha_j = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2+\omega \\ -\gamma_2-\omega & 1-\kappa+\gamma_1 \end{pmatrix}$$



Convergence $\kappa = -\frac{1}{2}\nabla \cdot \boldsymbol{\alpha}$

Shear

Rotation

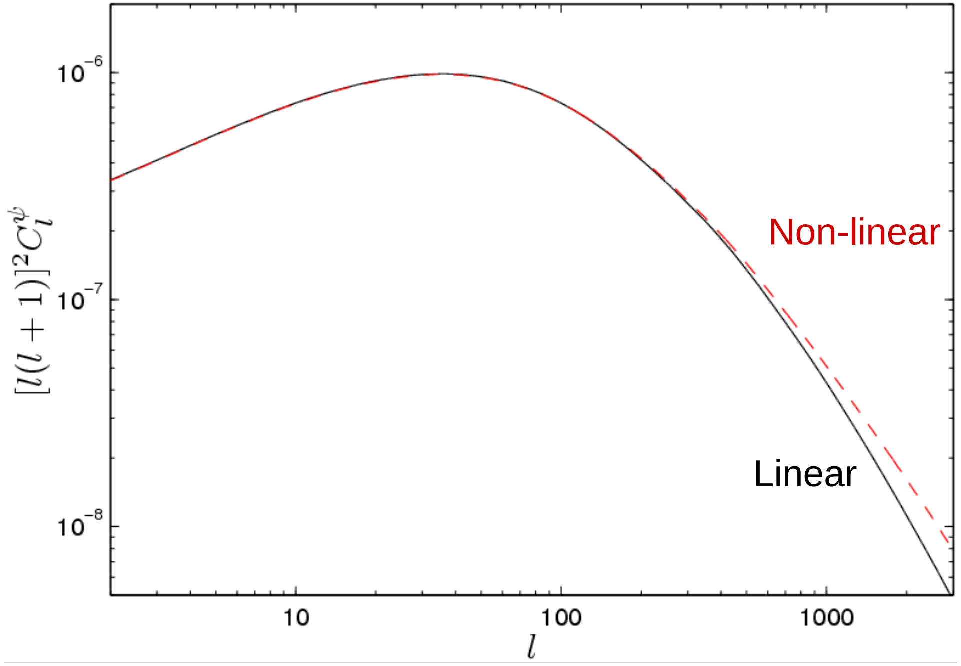
Rotation $\omega = 0$ from scalar perturbations in linear perturbation theory

$$\omega = 0 \Rightarrow \alpha = \nabla\psi$$

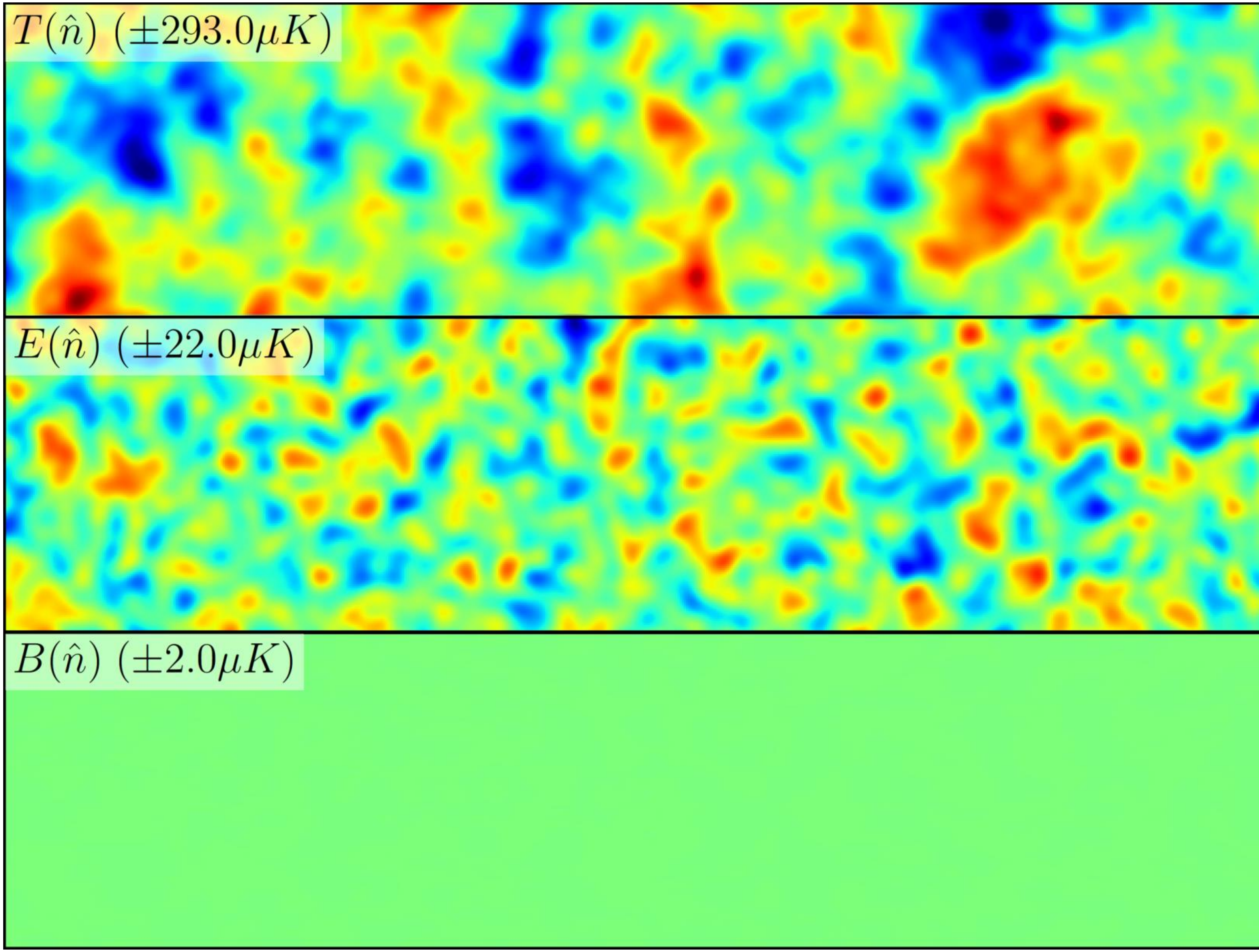
Deflection angle power spectrum

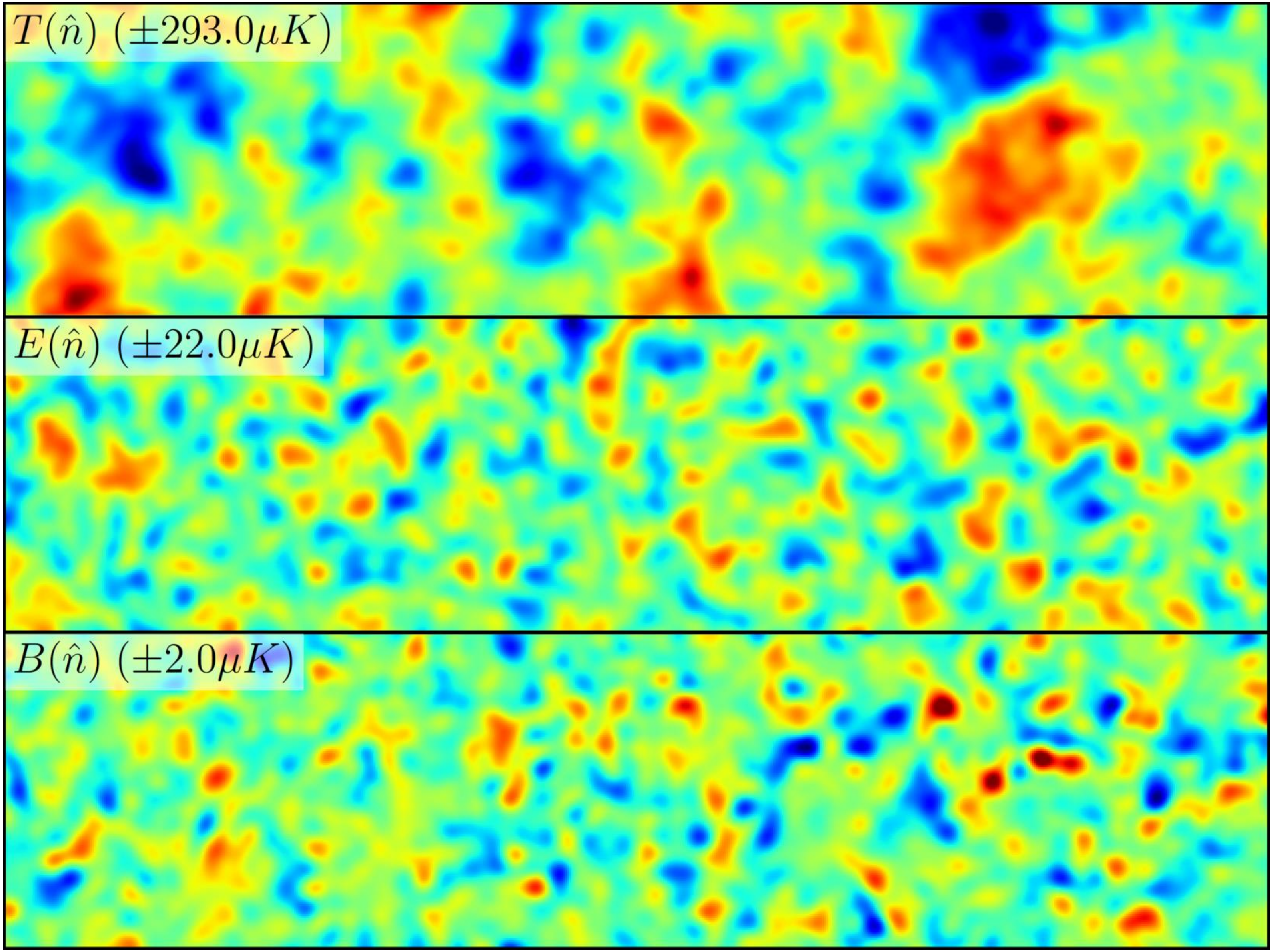
On small scales
(Limber approx. $k\chi \sim l$)

$$C_l^{\psi} \approx \frac{8\pi^2}{l^3} \int_0^{\chi_*} \chi \mathrm{d}\chi \, \mathcal{P}_\Psi(l/\chi; \eta_0 - \chi) \left(\frac{\chi_* - \chi}{\chi_* \chi} \right)^2$$



Deflections O(10^{-3}), but coherent on degree scales → important!


$T(\hat{n})$ ($\pm 293.0\mu K$)
$E(\hat{n})$ ($\pm 22.0\mu K$)
$B(\hat{n})$ ($\pm 2.0\mu K$)



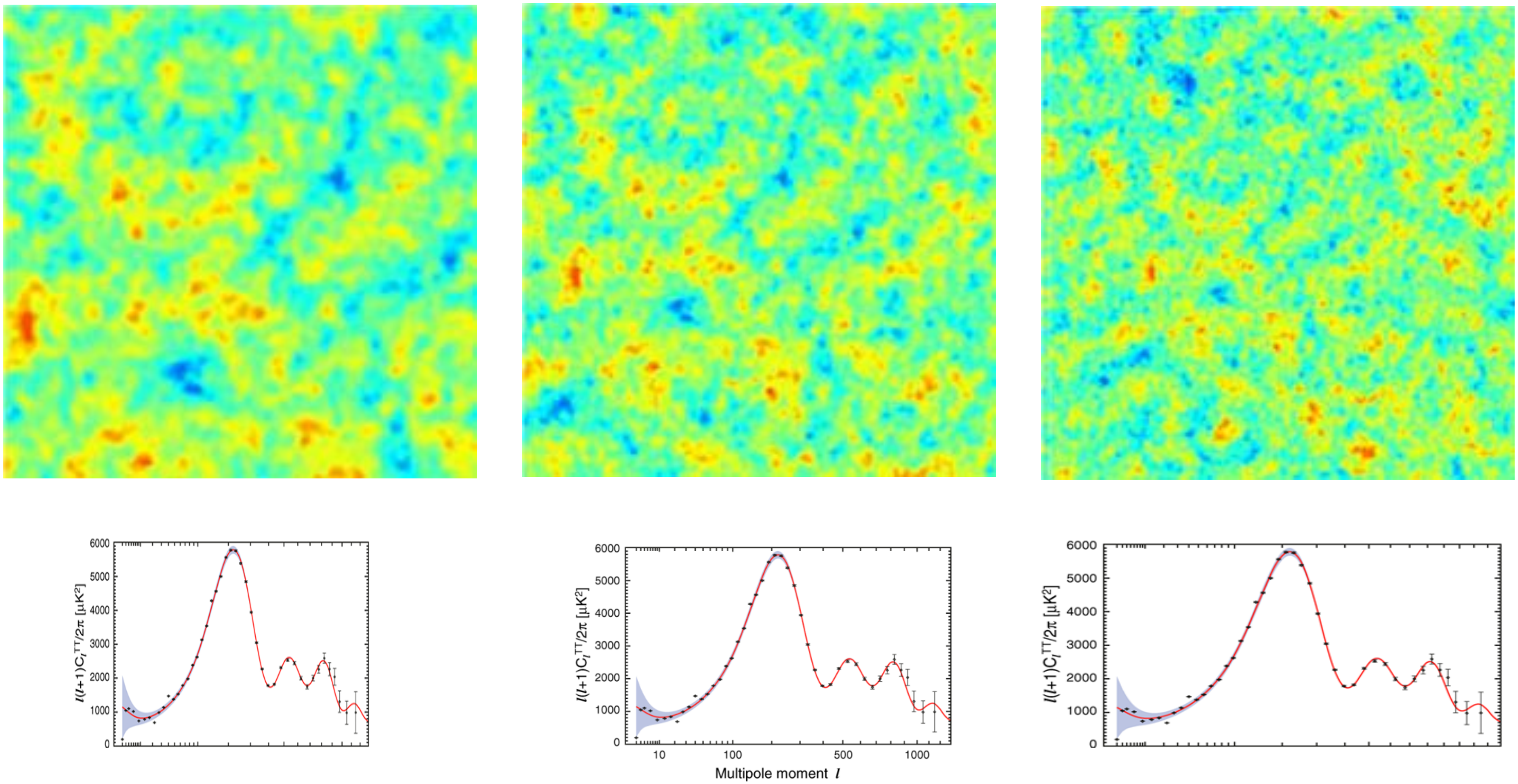
$T(\hat{n})$ ($\pm 293.0 \mu K$)
$E(\hat{n})$ ($\pm 22.0 \mu K$)
$B(\hat{n})$ ($\pm 2.0 \mu K$)

Local effect of lensing on the power spectrum

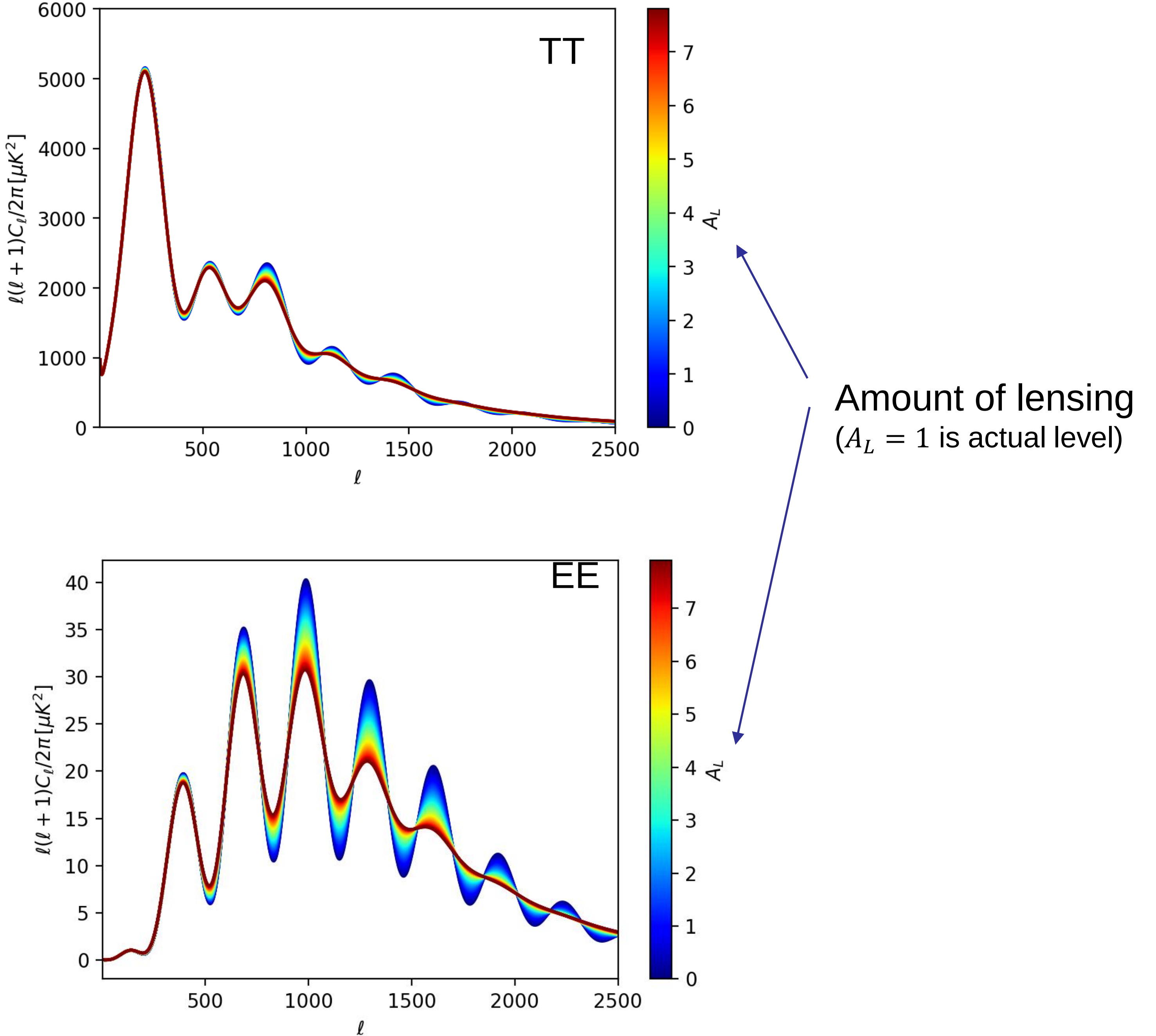
Magnified

Unlensed

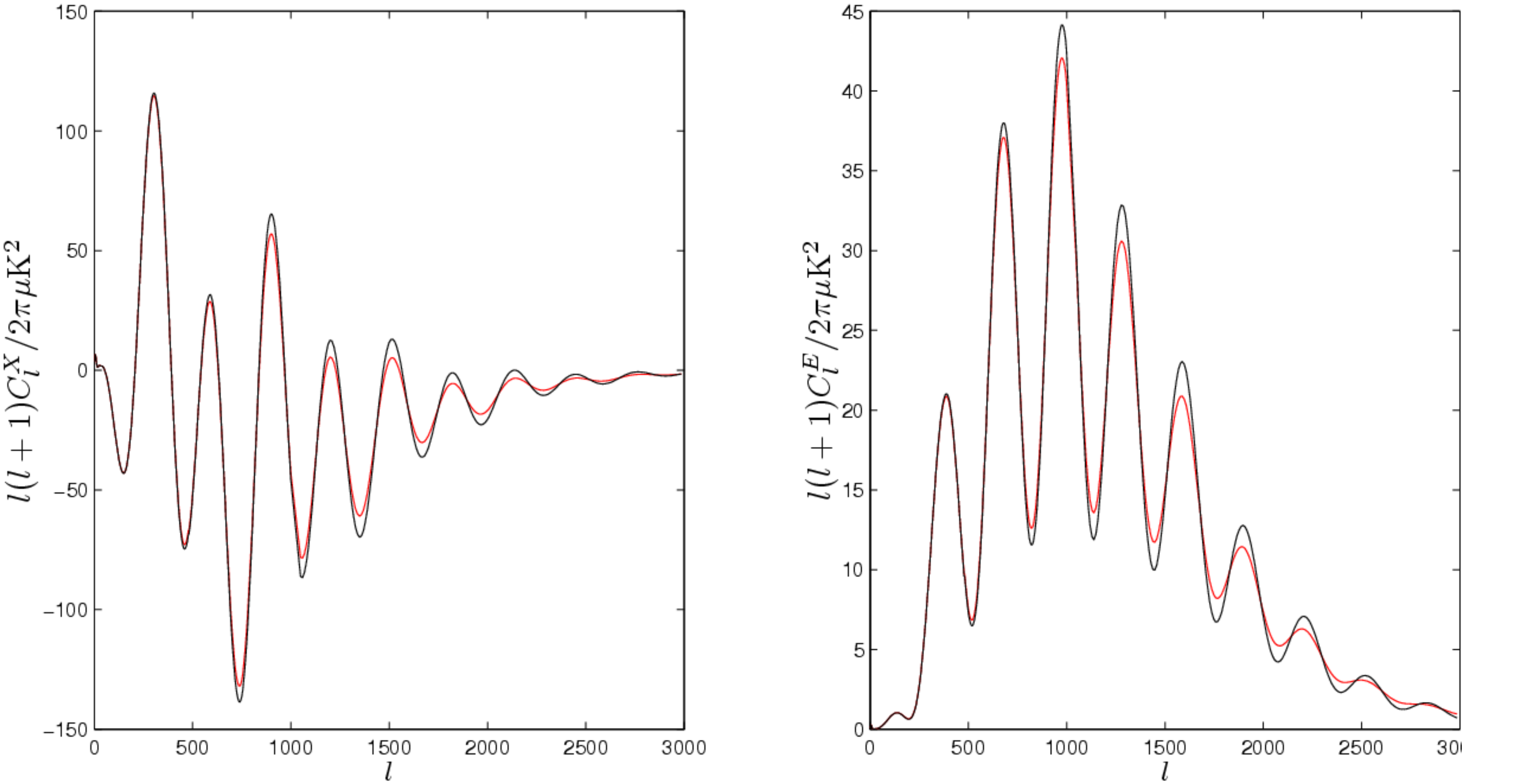
Demagnified



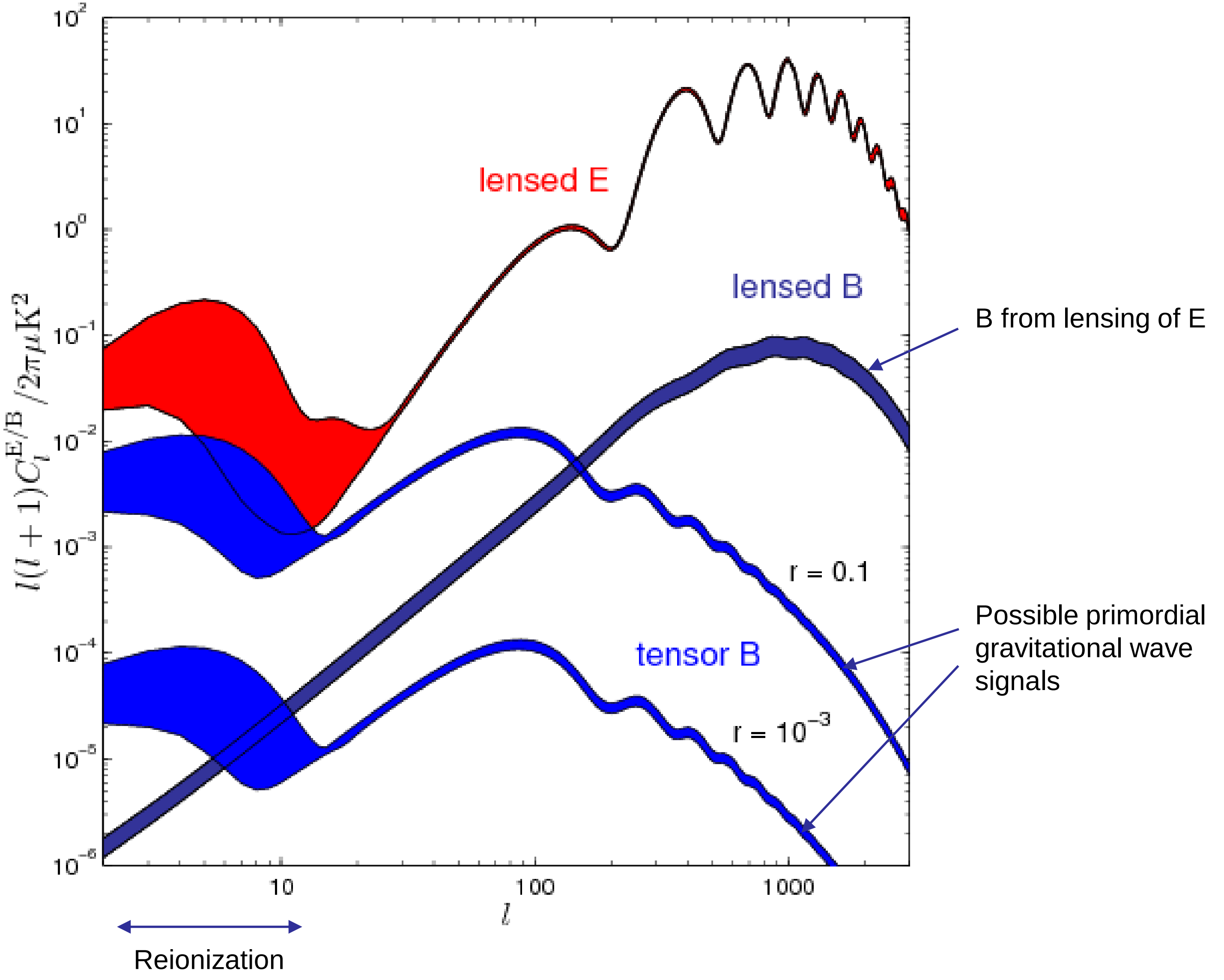
Averaged over the sky, lensing smooths out the power spectrum



Effect on TE and EE polarization spectra



Polarization power spectra



Outline

1. How can we reconstruct the lensing?

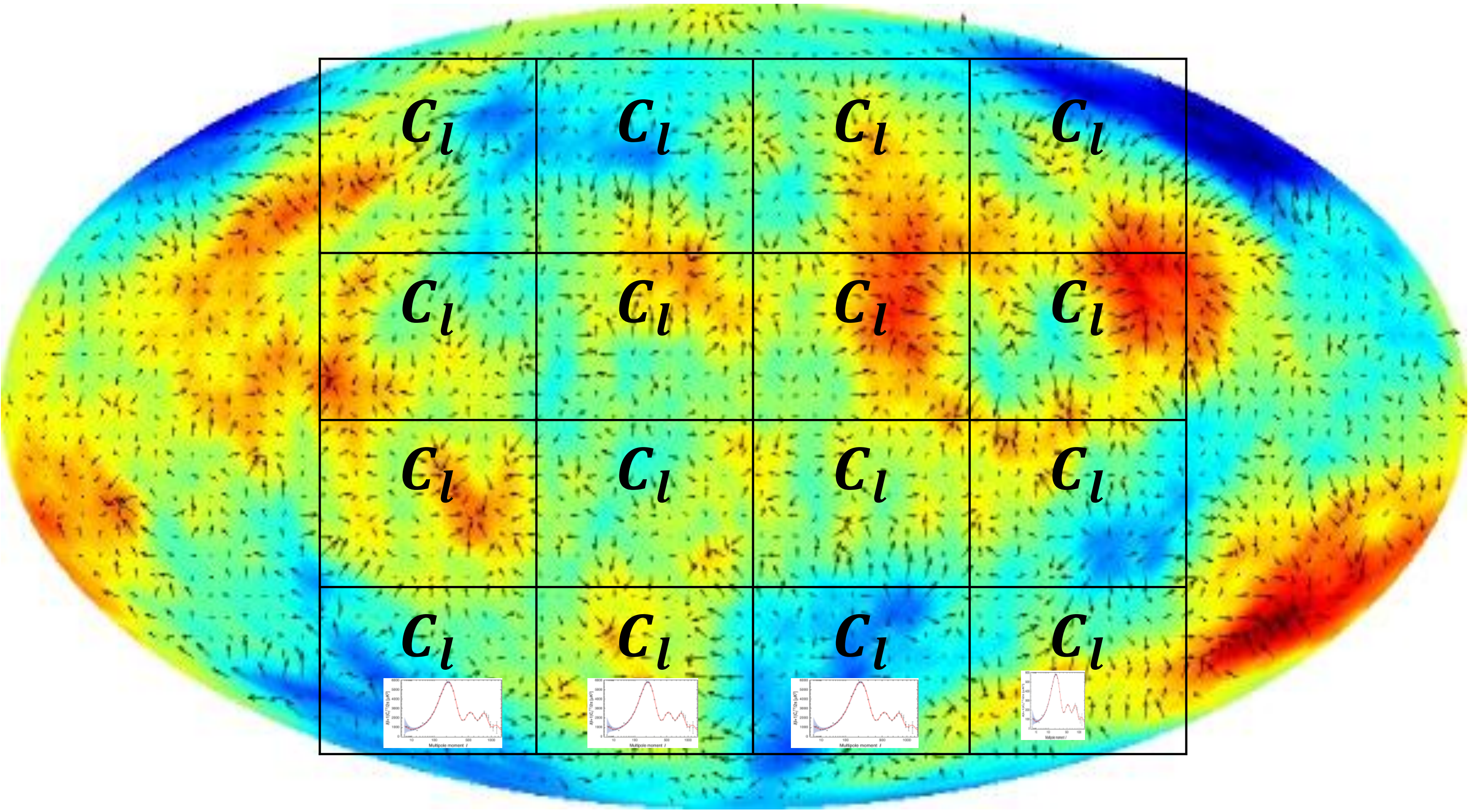
   - gives a powerful cosmological probe
   (z~2 peak; constraints on LCDM, massive neutrinos, etc.)

2. Can we then delens?

   - unsmooth the power spectra, clean the lensing B modes

3. How well can we delens in future?

Lensing reconstruction (concept)



Measure spatial variations in magnification and shear

Use assumed unlensed spectrum, and unlensed statistical isotropy

Lensing Reconstruction – Quadratic Estimators

- Fixed lenses introduce statistically-anisotropic correlations:

$$\Delta\langle X_{l_1 m_1} Y_{l_2 m_2}\rangle_{\rm CMB} = \sum_{LM} (-1)^M \begin{pmatrix} l_1 & l_2 & L \\ m_1 & m_2 & -M \end{pmatrix} \mathcal{W}^{XY}_{l_1 l_2 L} \phi_{LM}$$

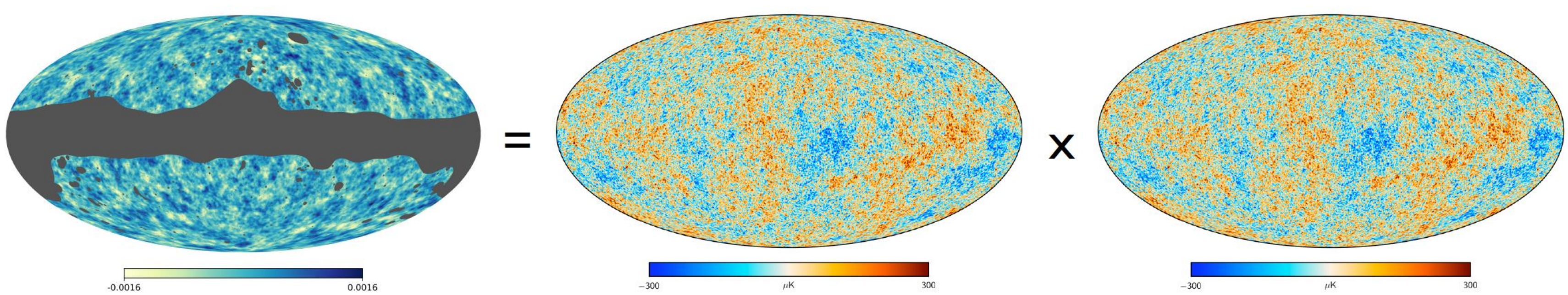
- Noisy lensing estimates from quadratic CMB combinations:

$$\hat{\phi}_{LM} = \frac{(-1)^M}{2} \frac{1}{\mathcal{R}^{XY}_L} \sum_{l_1 m_1, l_2 m_2} \begin{pmatrix} l_1 & l_2 & L \\ m_1 & m_2 & -M \end{pmatrix} \left[\mathcal{W}^{XY}_{l_1 l_2 L}\right]^* \bar{X}_{l_1 m_1} \bar{Y}_{l_2 m_2}$$

Normalisation

Known lensing-induced correlations

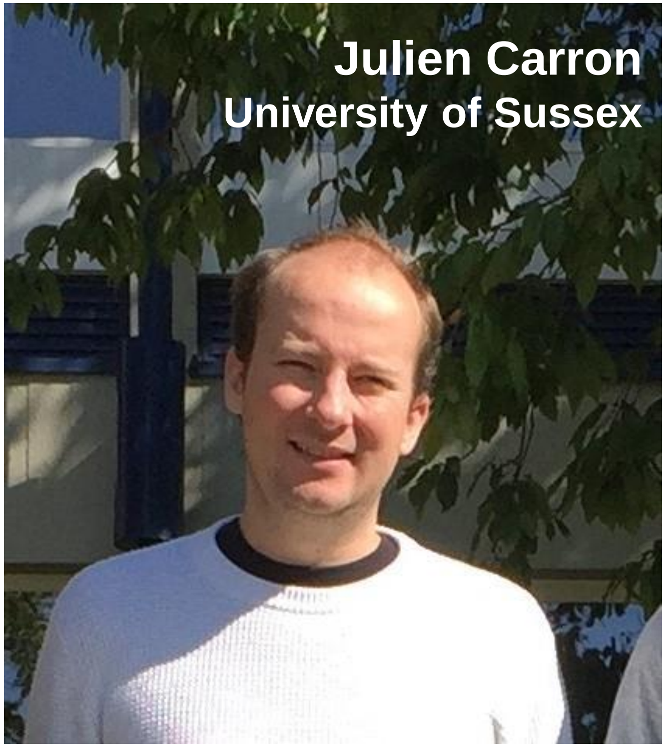
Inverse-variance-weighted CMB fields



Planck Lensing 2018 arXiv:1807.06210

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

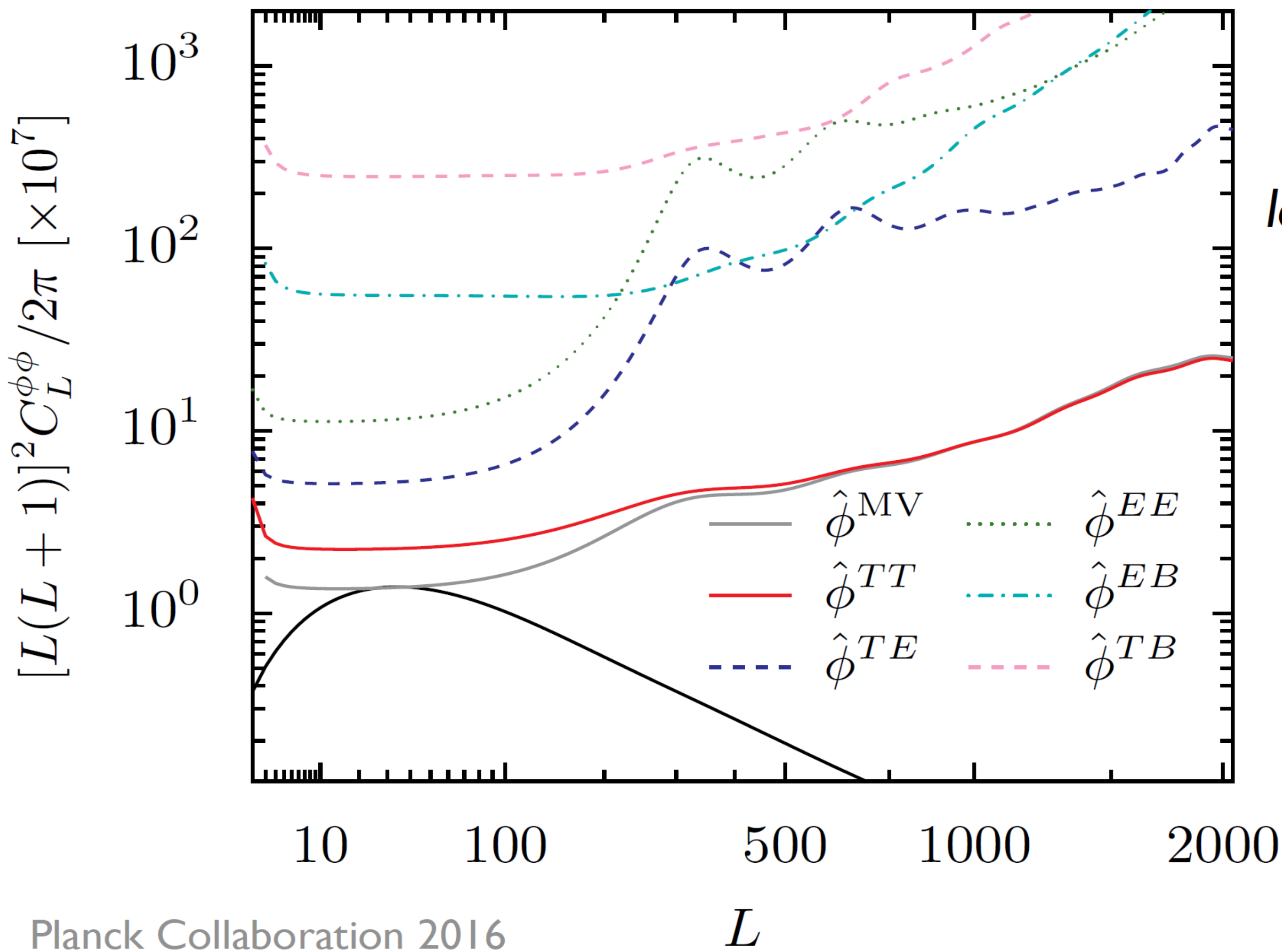
Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.



(+ thanks to Anthony Challinor for a few slides)

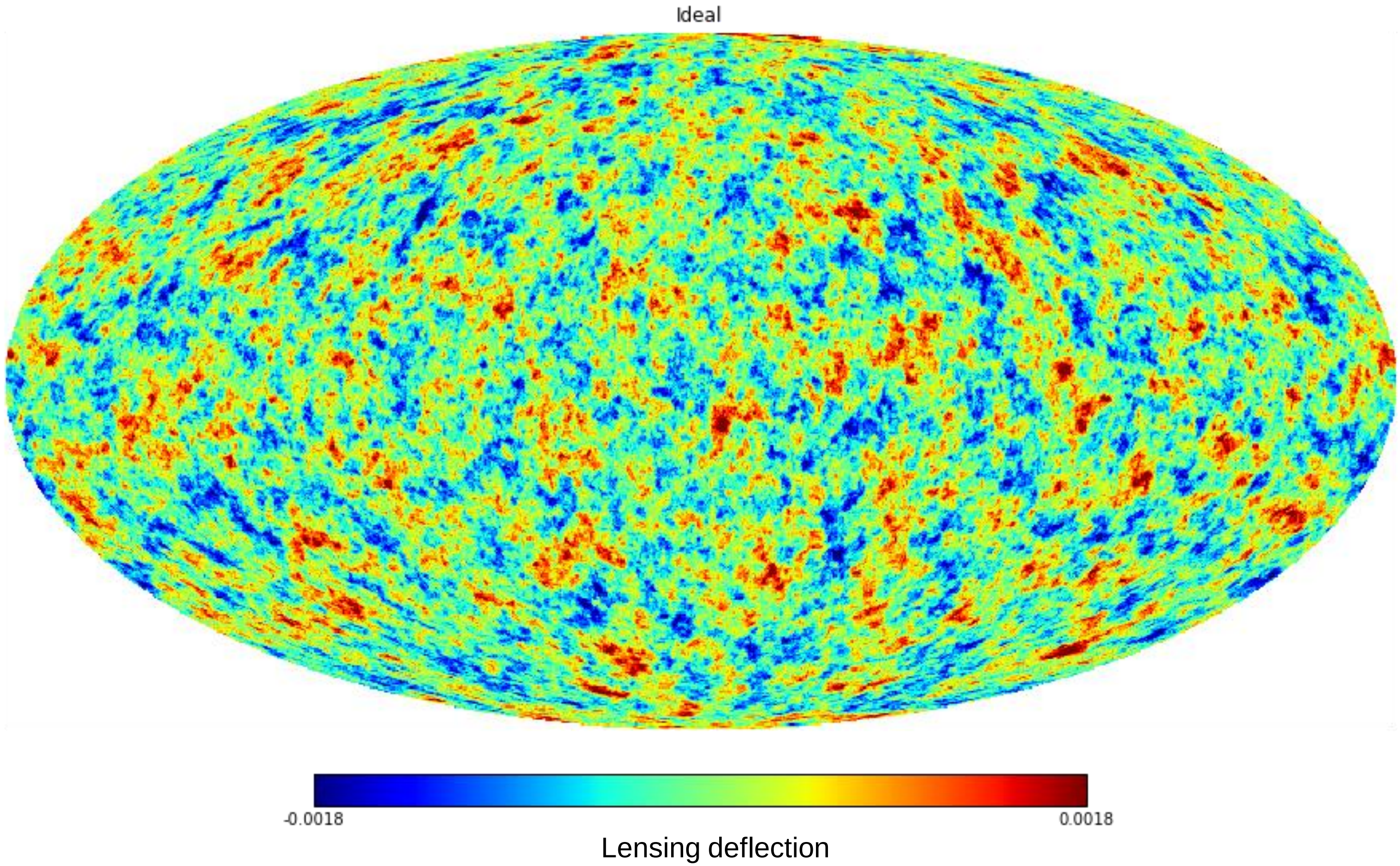
Planck lensing reconstruction noise

(instrumental noise + cosmic variance of unlensed T/E)

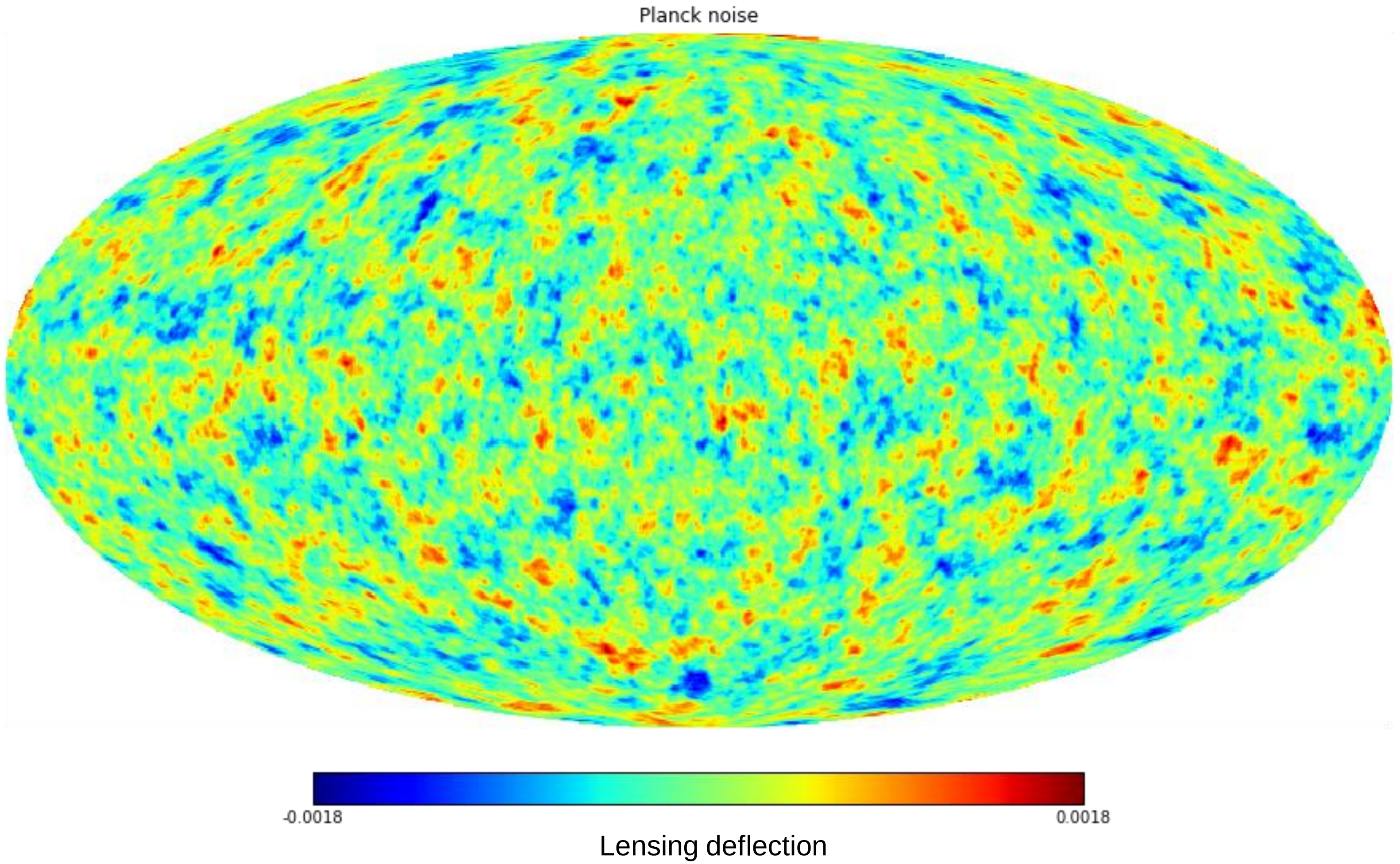


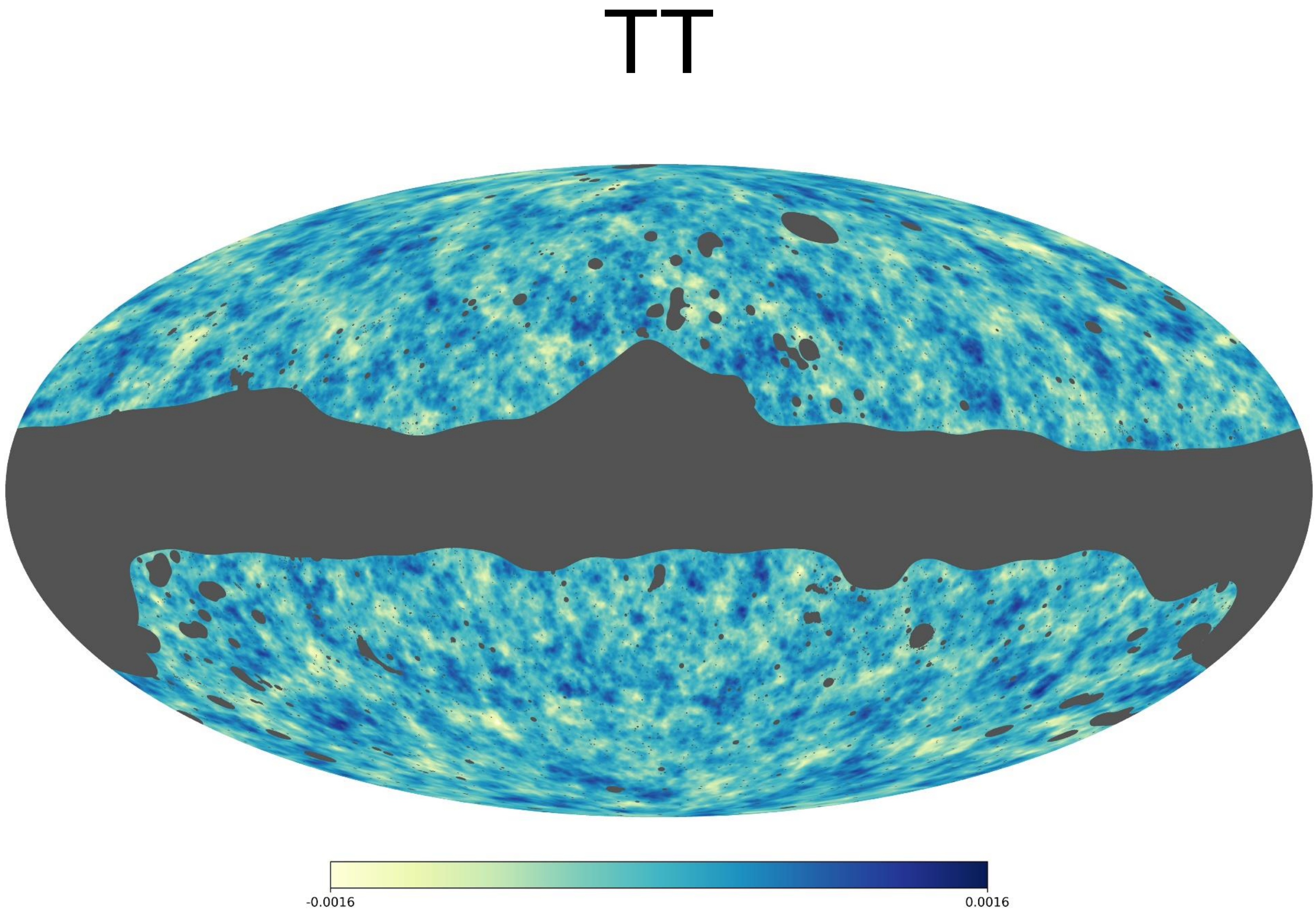
Planck Collaboration 2016

True simulation input

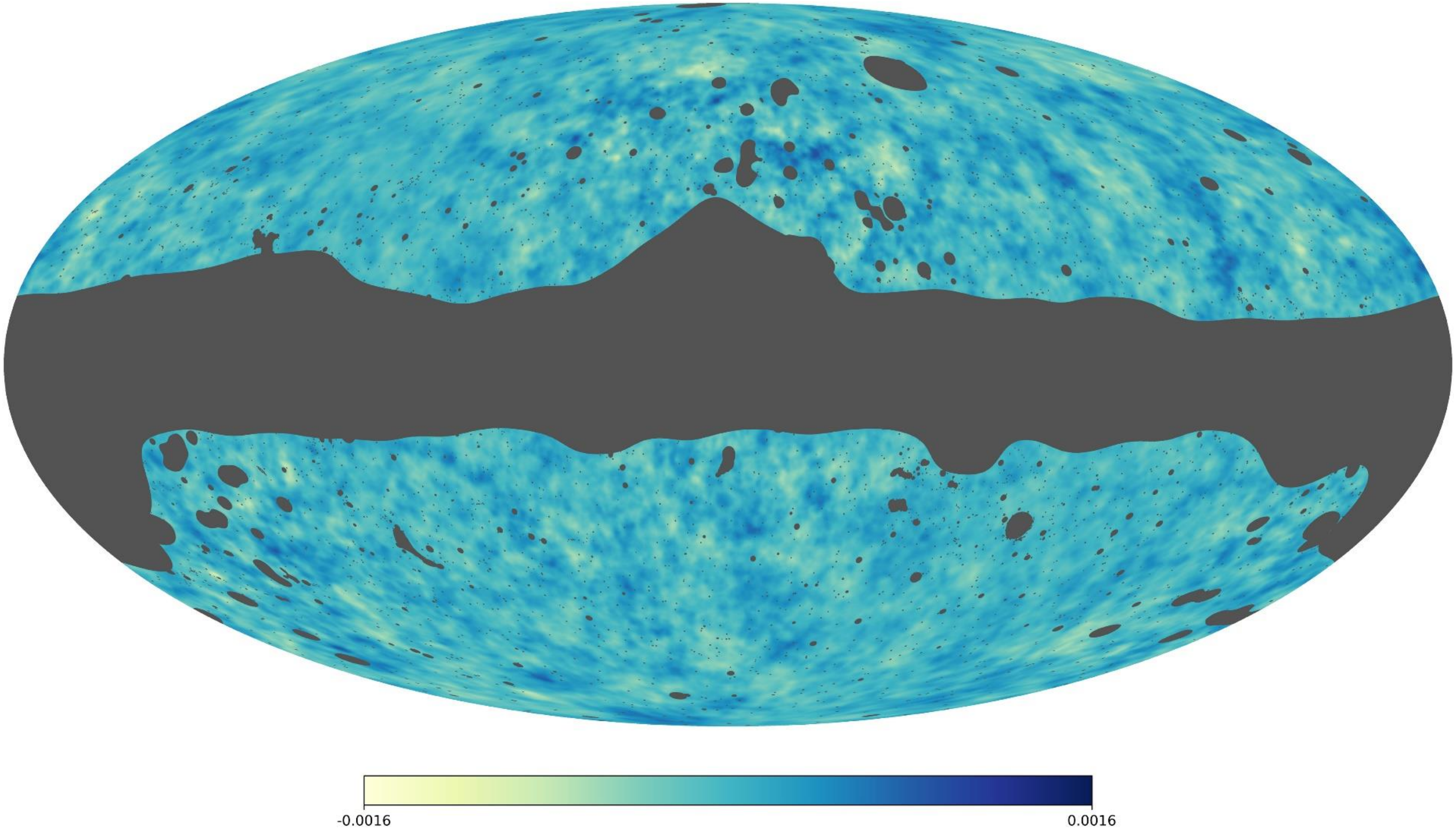


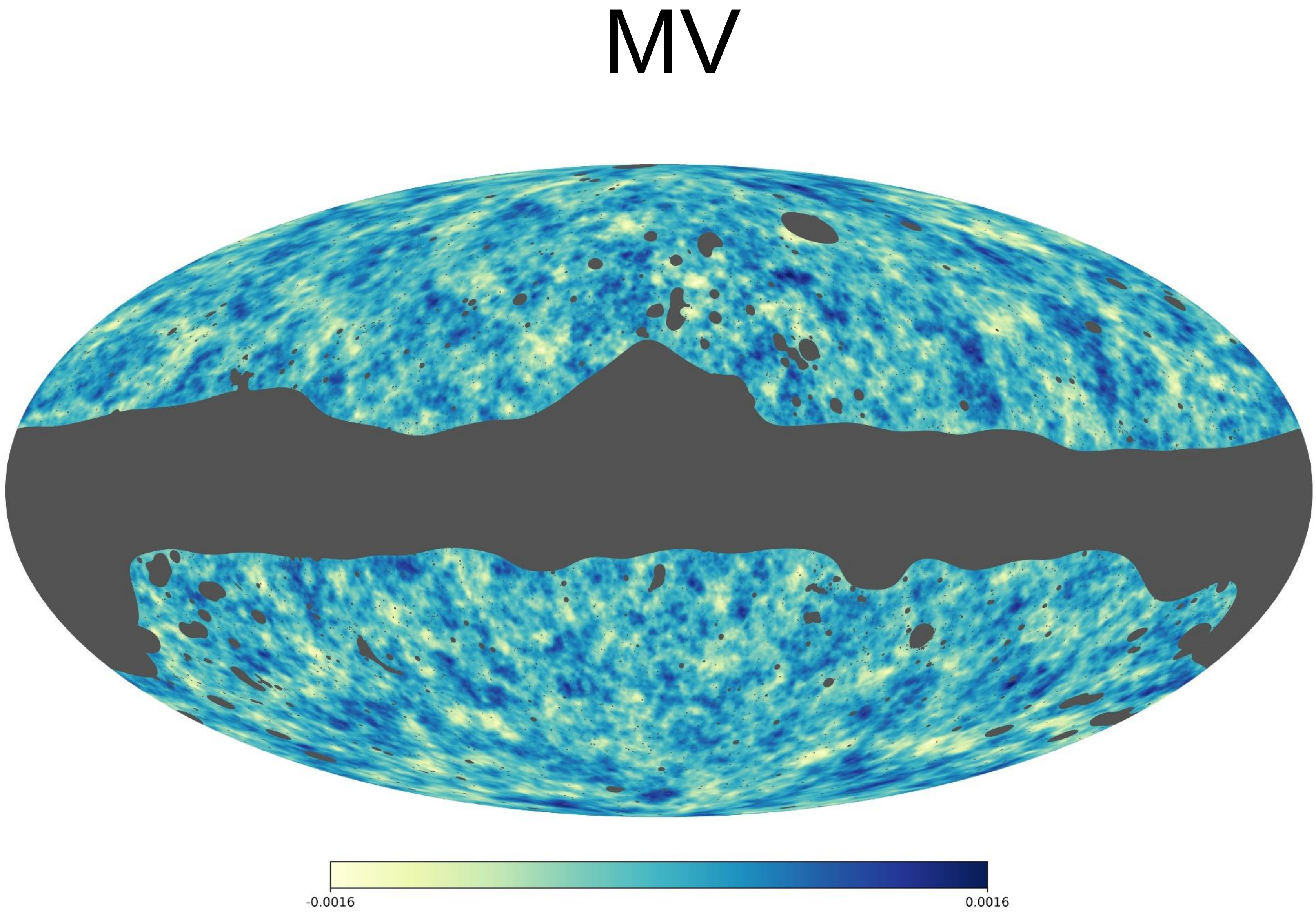
Simulated Planck lensing reconstruction

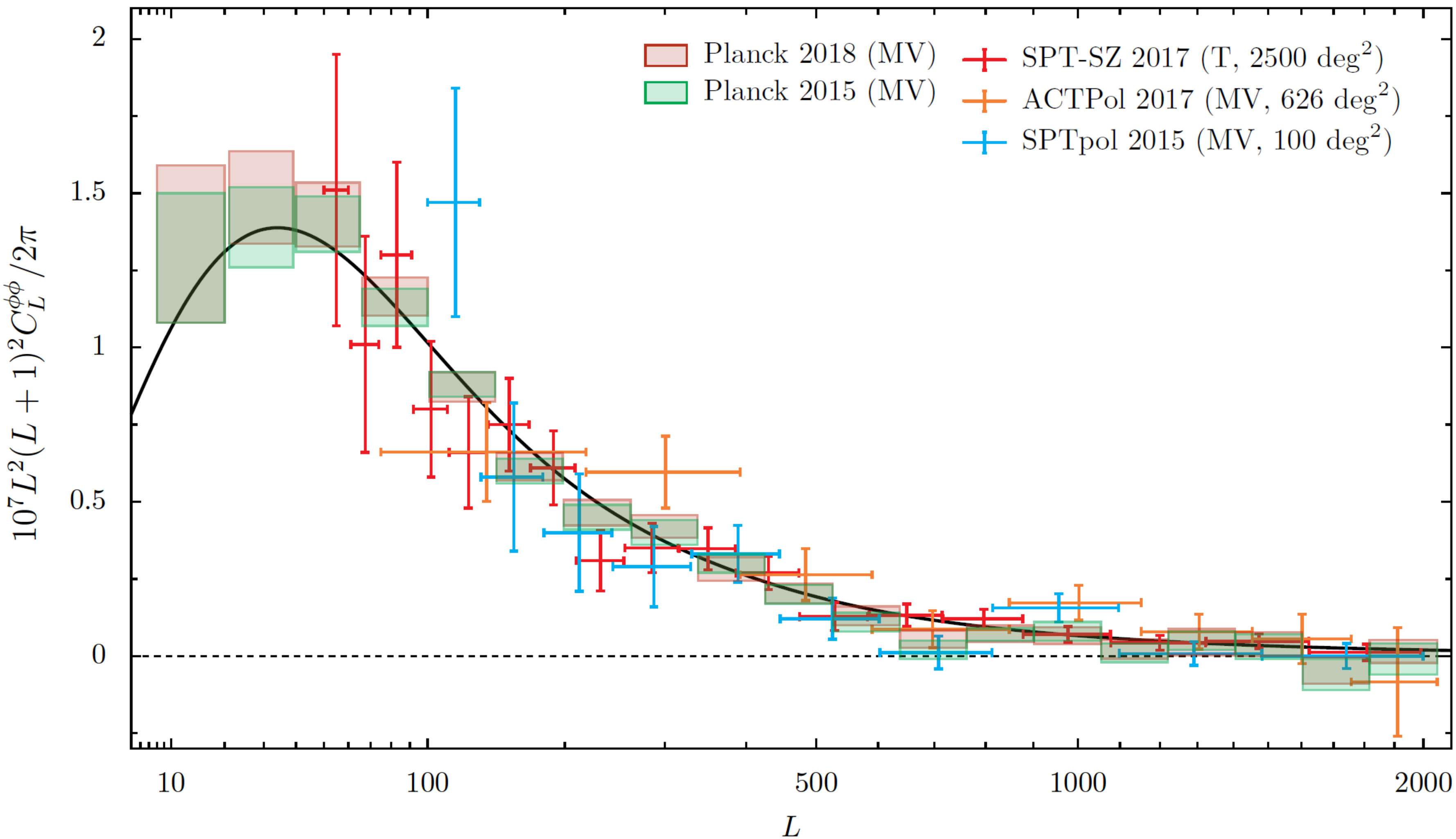



TT
-0.0016
0.0016

Polarization

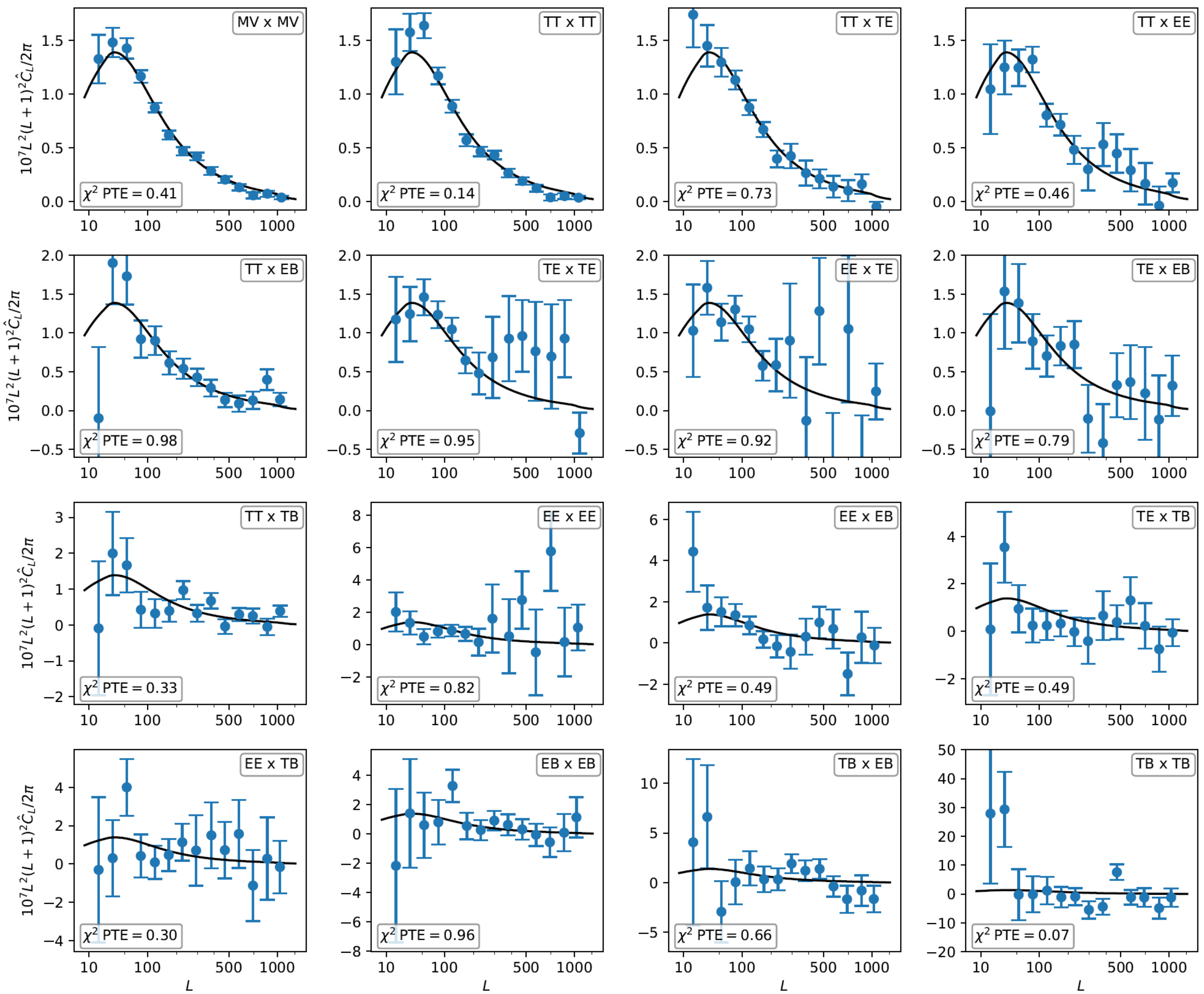



MV
-0.0016
0.0016



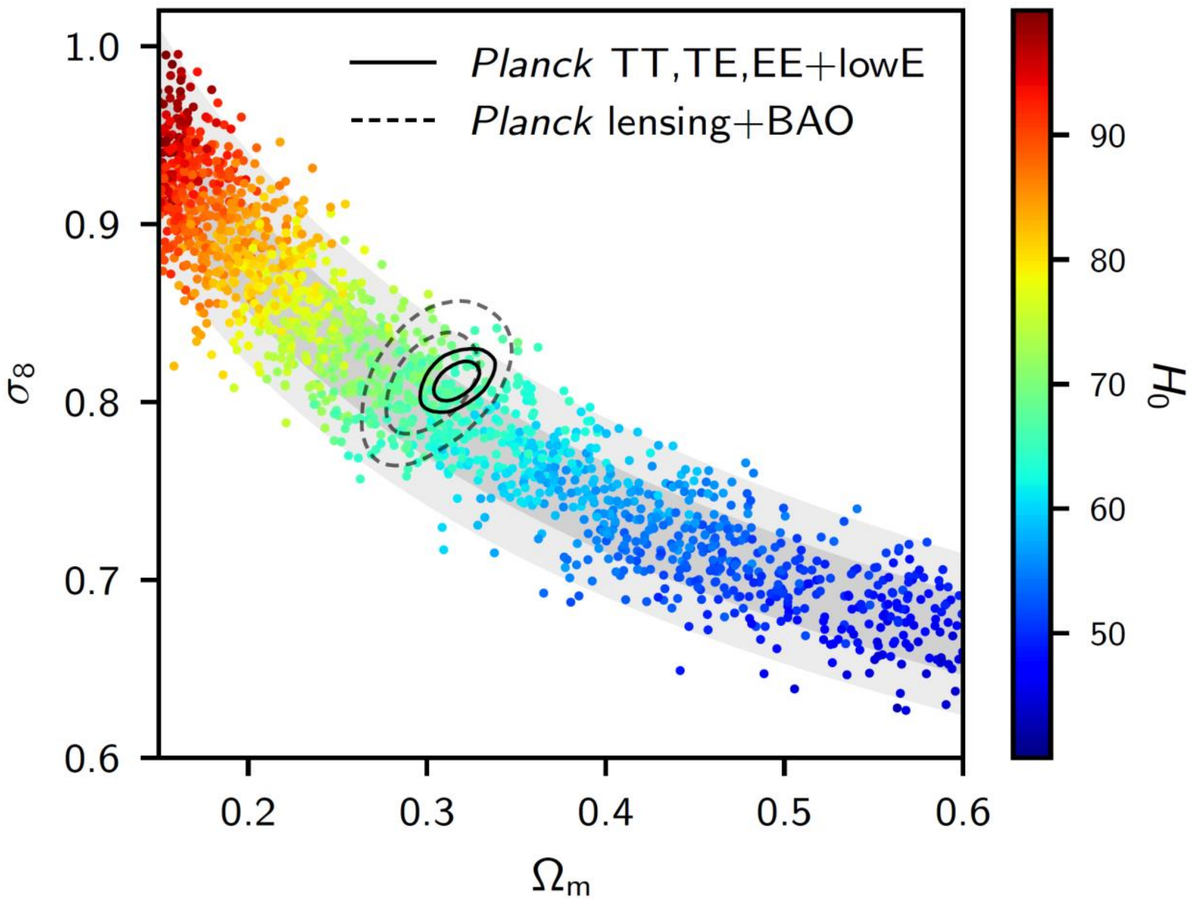
Planck 2018 (MV)
Planck 2015 (MV)
SPT-SZ 2017 (T, 2500 deg^2)
ACTPol 2017 (MV, 626 deg^2)
SPTpol 2015 (MV, 100 deg^2)
$10^7 L^2(L+1)^2 C_L^{\phi\phi}/2\pi$
2
1.5
1
0.5
0
10
100
500
1000
2000
L

Individual estimators



Lensing LCDM parameters

CMB lensing best measures $\sim \sigma_8 \Omega_m^{0.25} = 0.589 \pm 0.020$.



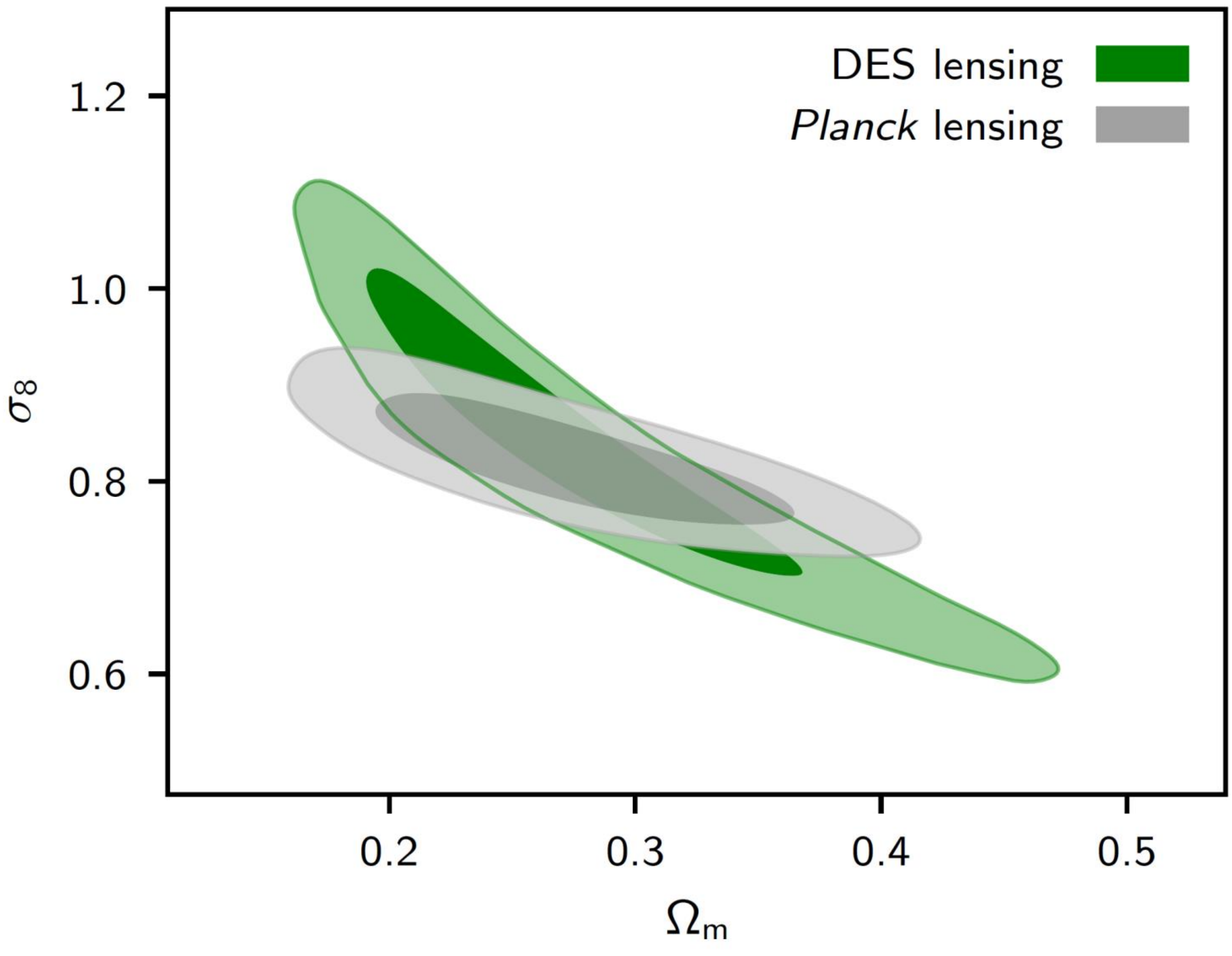
"Lensing-only" priors:

$\Omega_b h^2 = 0.0222 \pm 0.0005,$

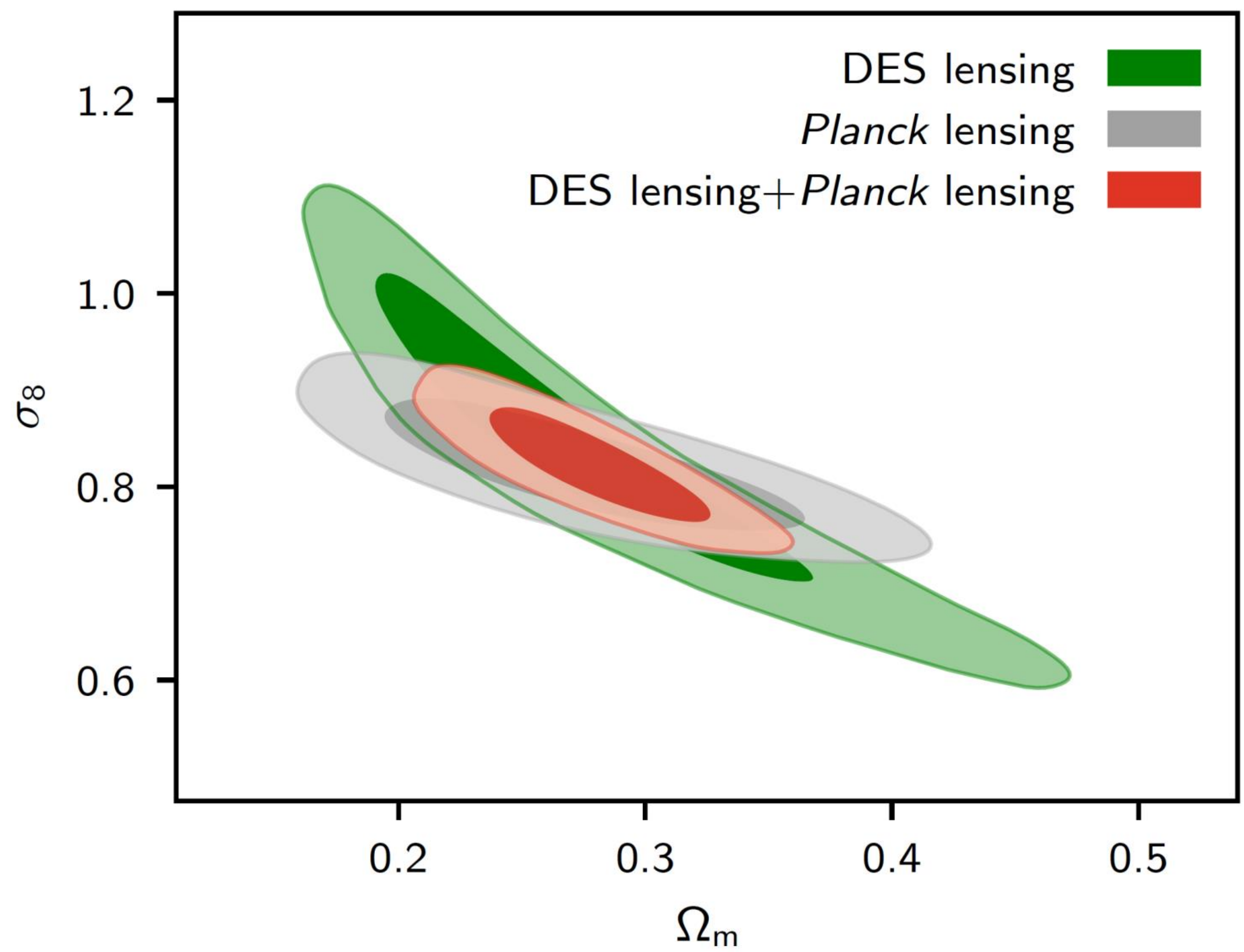
$n_s = 0.96 \pm 0.02$

$0.4 < h < 1$

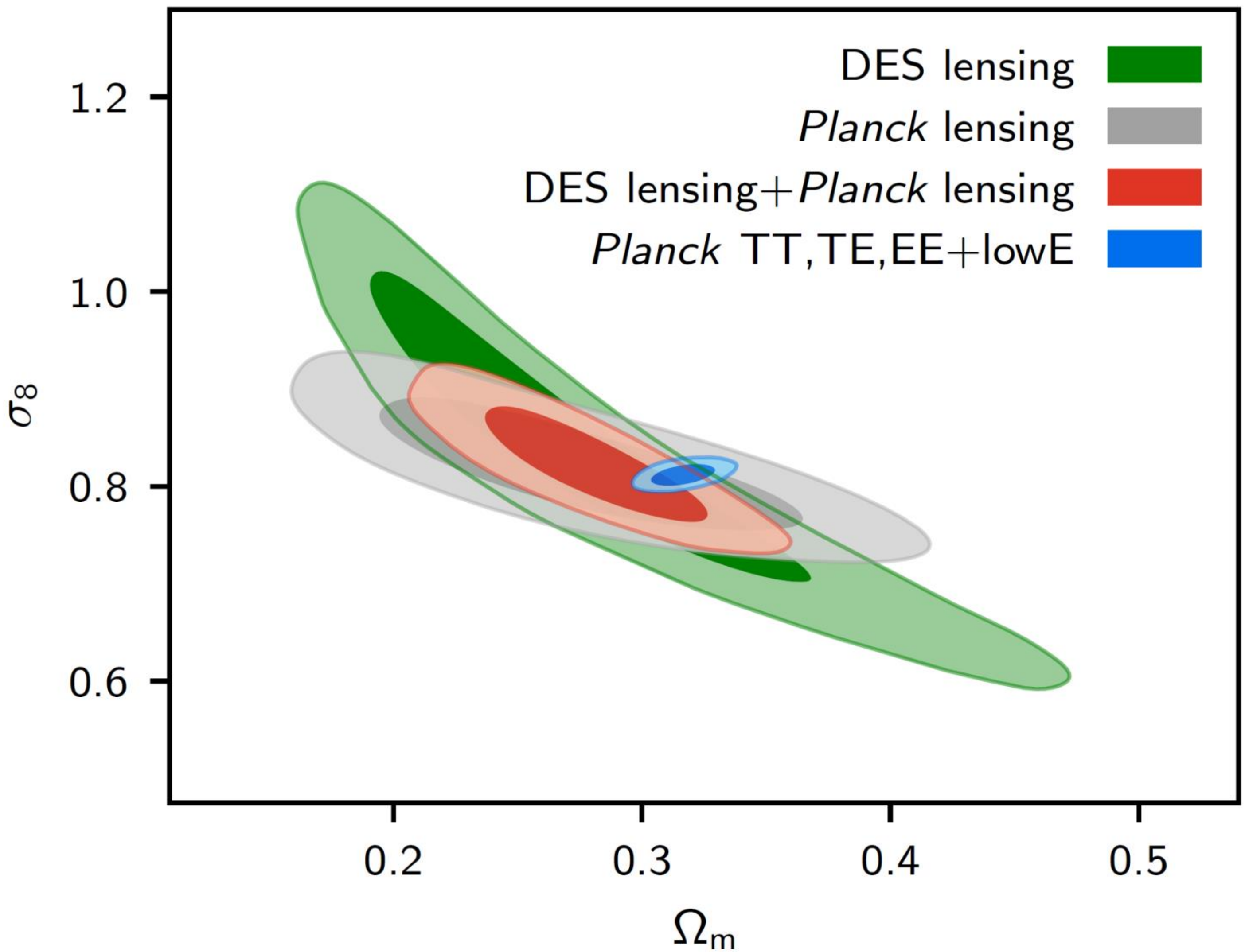
$$\left. \begin{aligned} H_0 &= 67.9^{+1.2}_{-1.3}\ \mathrm{km\ s^{-1} Mpc^{-1}}, \\ \sigma_8 &= 0.811 \pm 0.019, \\ \Omega_m &= 0.303^{+0.016}_{-0.018}, \end{aligned} \right\} \quad 68\,\%,\ \text{lensing+BAO}$$



DES lensing from Troxel et al. (DES Collaboration 2017, 10 nuisance parameters marginalized)

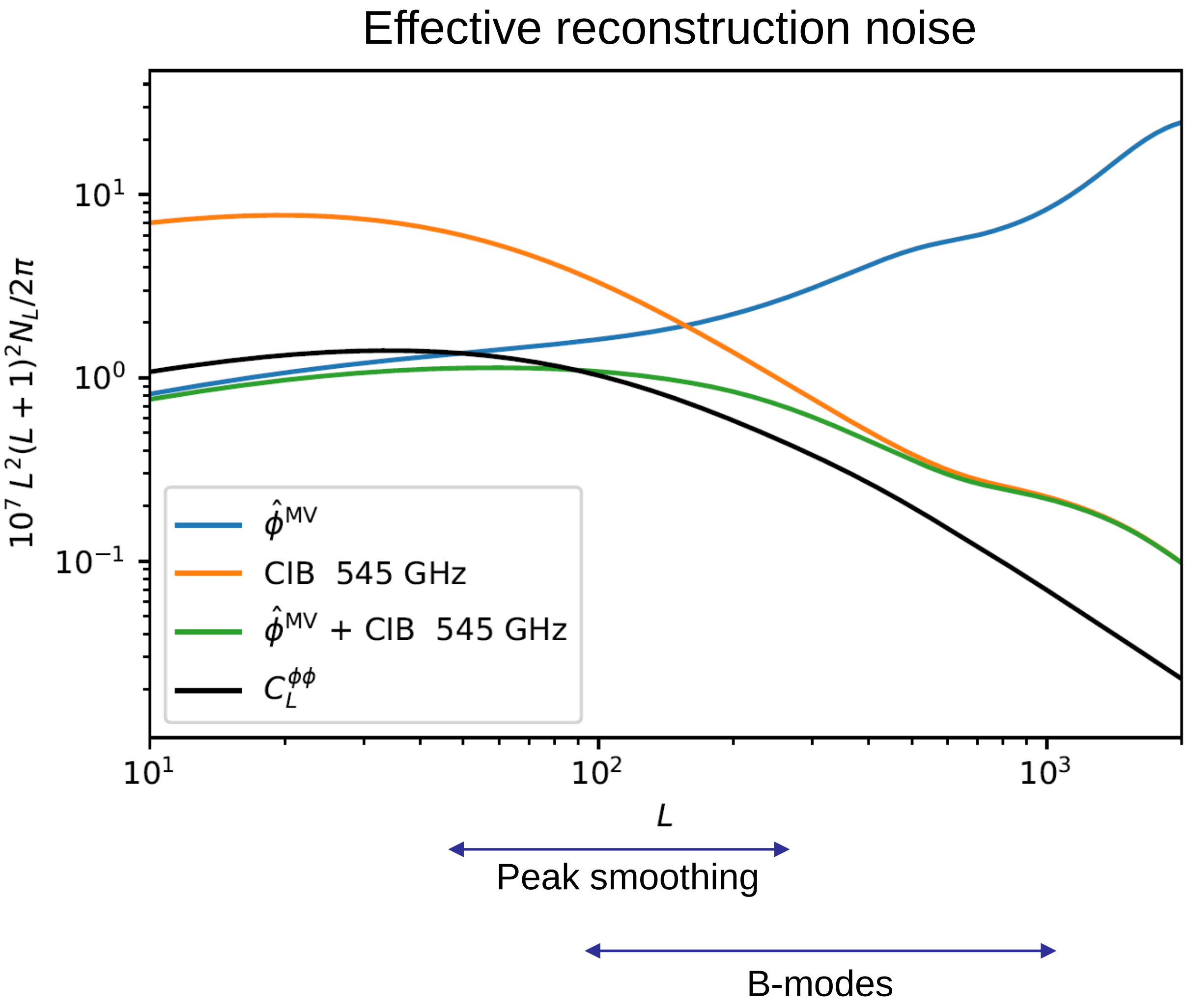


DES lensing
Planck lensing
DES lensing+*Planck* lensing
1.2
1.0
0.8
0.6
σ_8
0.2
0.3
0.4
0.5
Ω_m

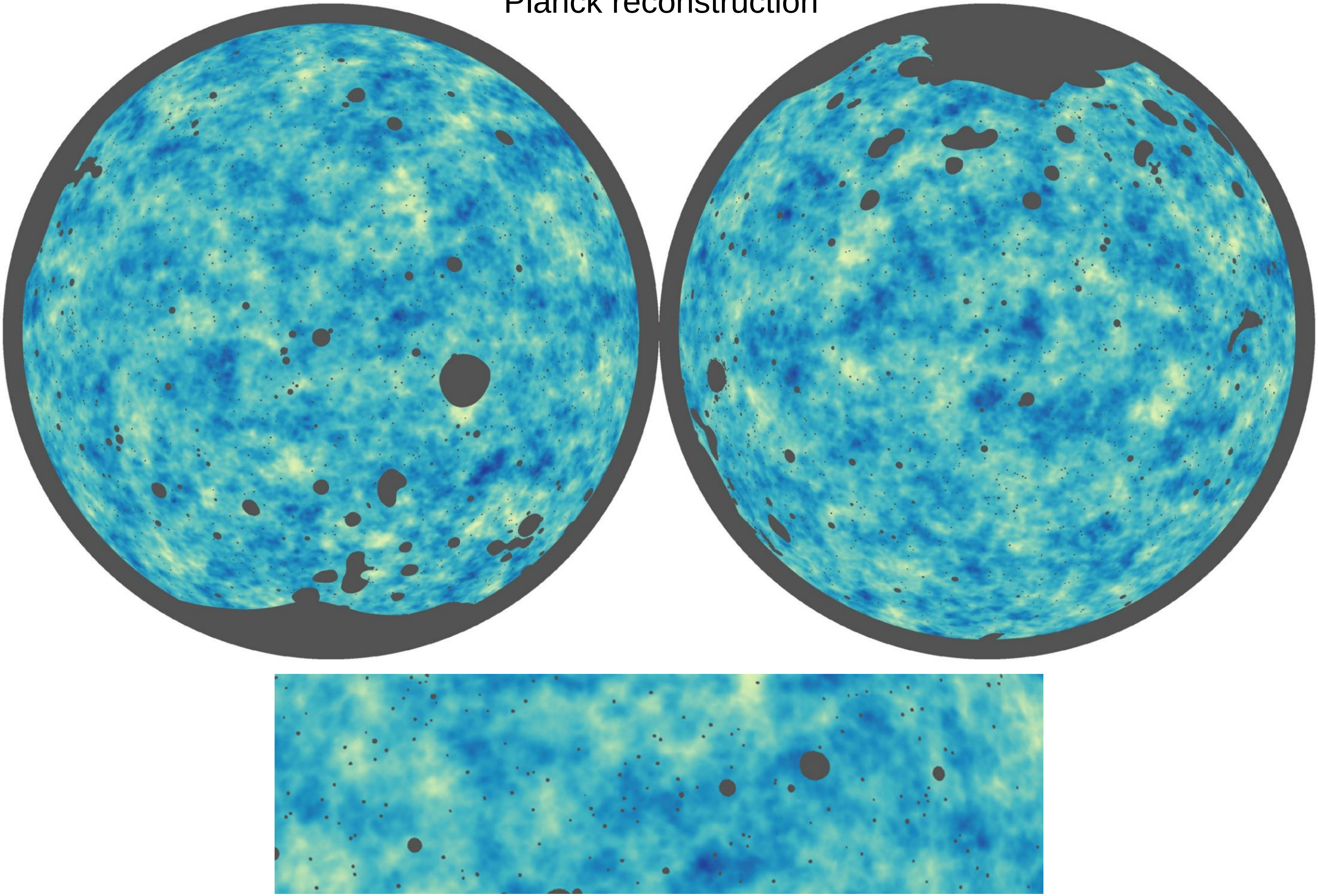

DES lensing
Planck lensing
DES lensing+Planck lensing
Planck TT,TE,EE+lowE
1.2
1.0
0.8
0.6
σ_8
0.2
0.3
0.4
0.5
Ω_m

Improving lensing reconstruction using Cosmic Infrared Background (CIB)

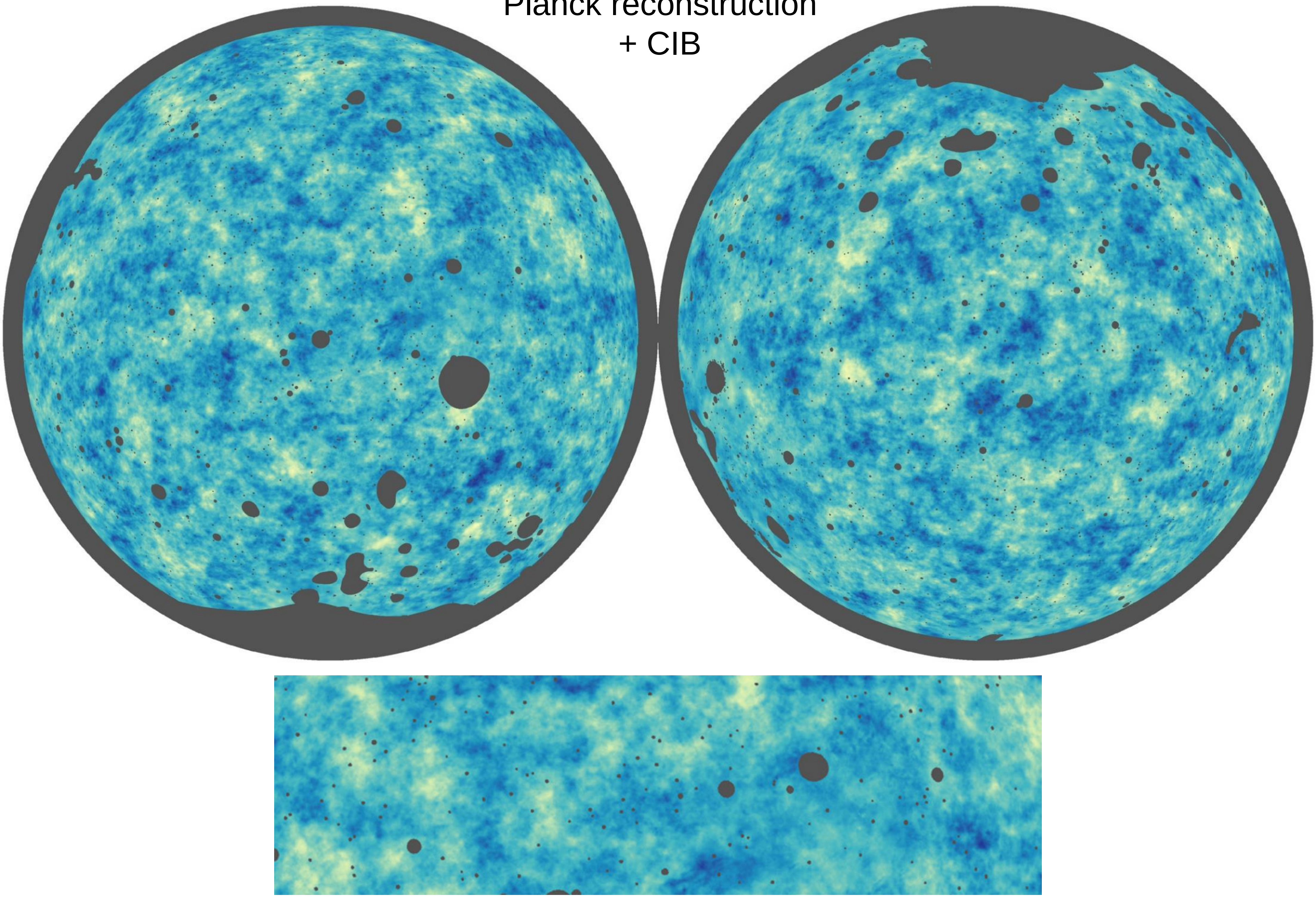
Use Planck GNILC 353, 545 GHz CIB maps as additional tracer of lensing potential



Planck reconstruction

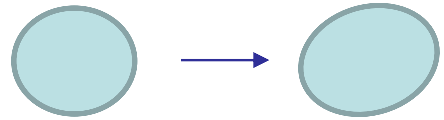


Planck reconstruction
+ CIB

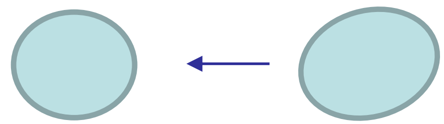


Delensing

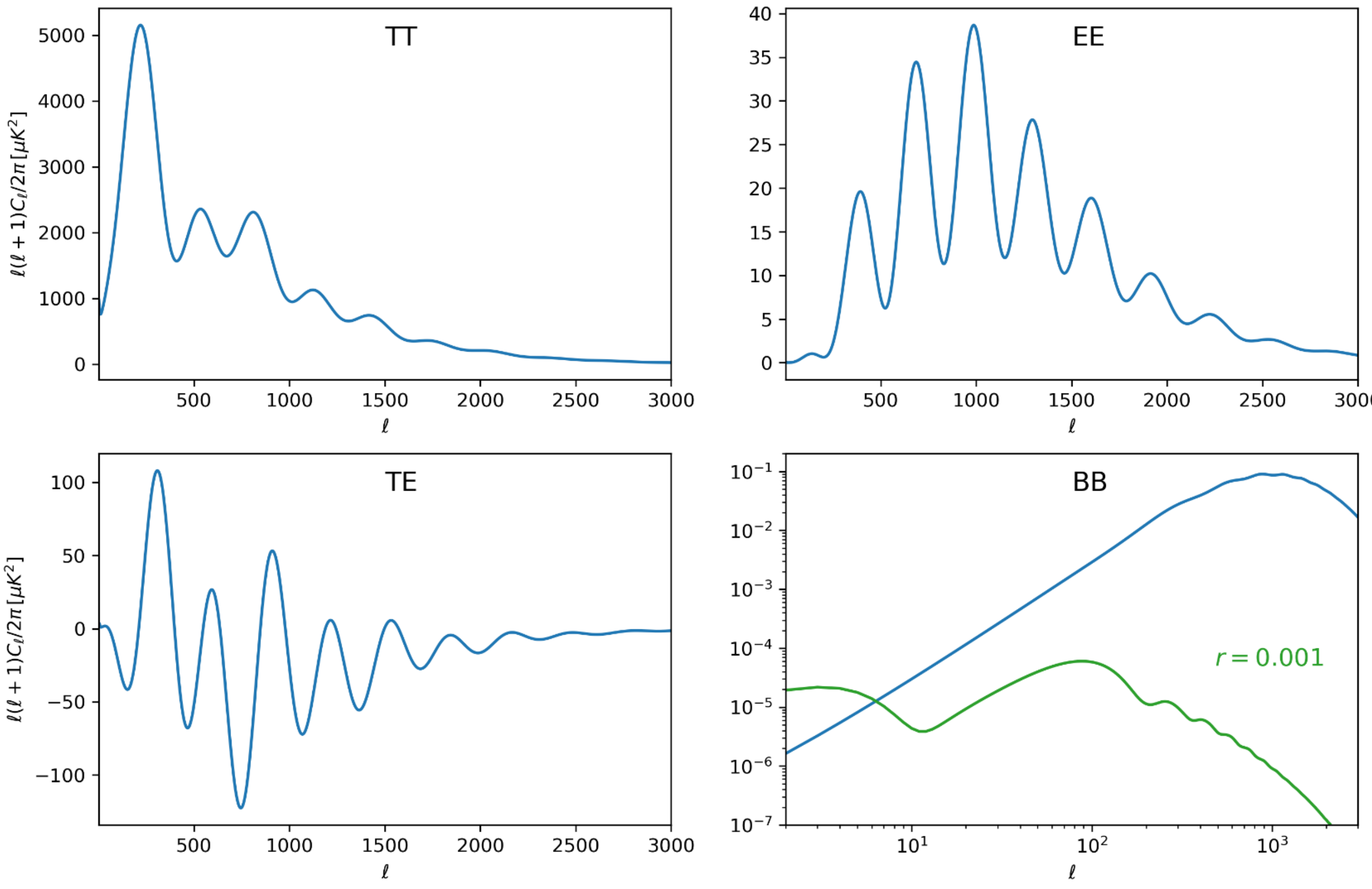
Lensing: $X^{\mathrm{len}}(\mathbf{n}) = X^{\mathrm{unl}}(\mathbf{n} + \boldsymbol{\alpha}(\boldsymbol{n}))$



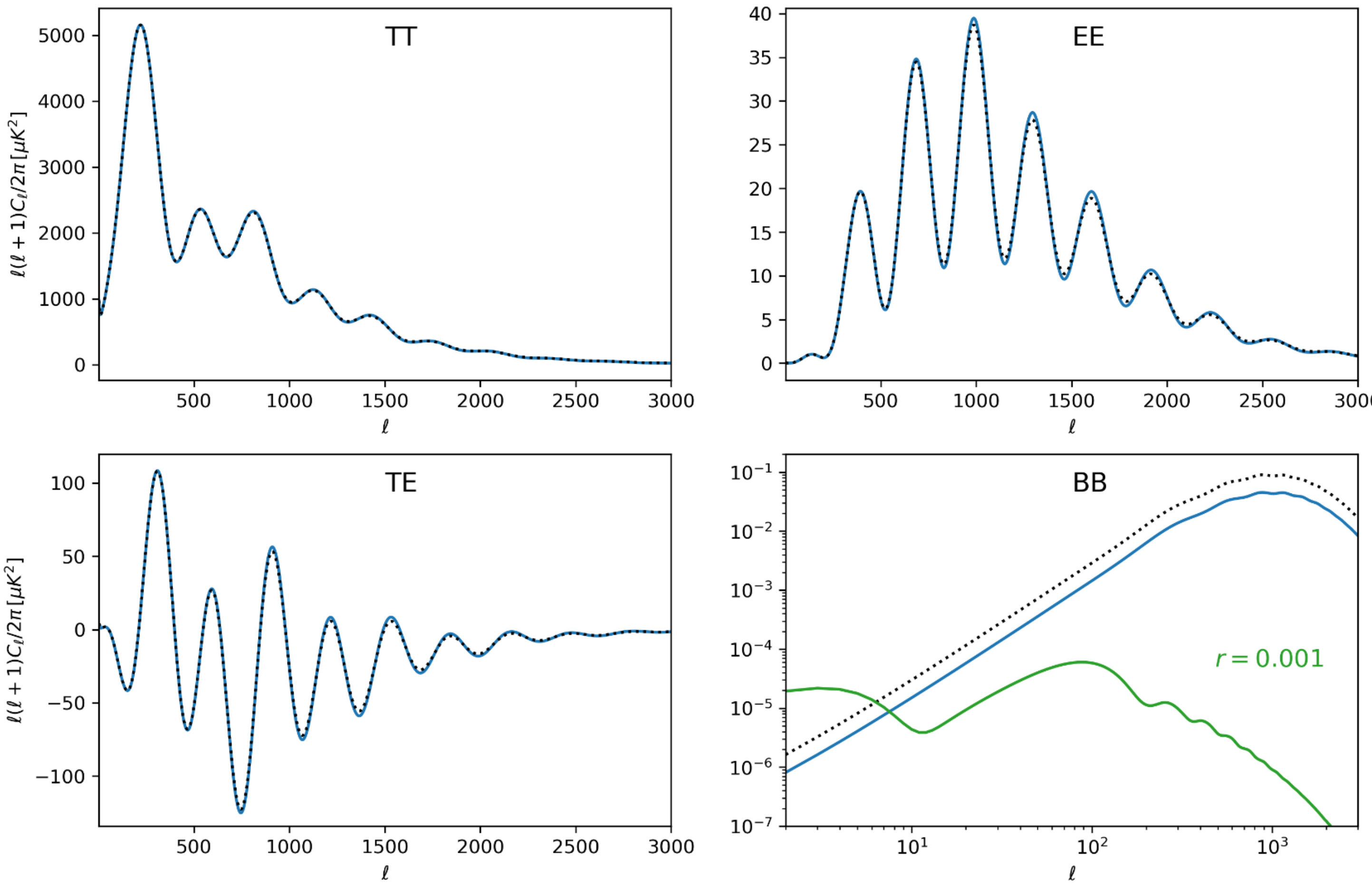
Delensing: $X^{\mathrm{delen}}(\mathbf{n}) \approx X^{\mathrm{len}}(\mathbf{n} - \boldsymbol{\alpha}(\boldsymbol{n}))$



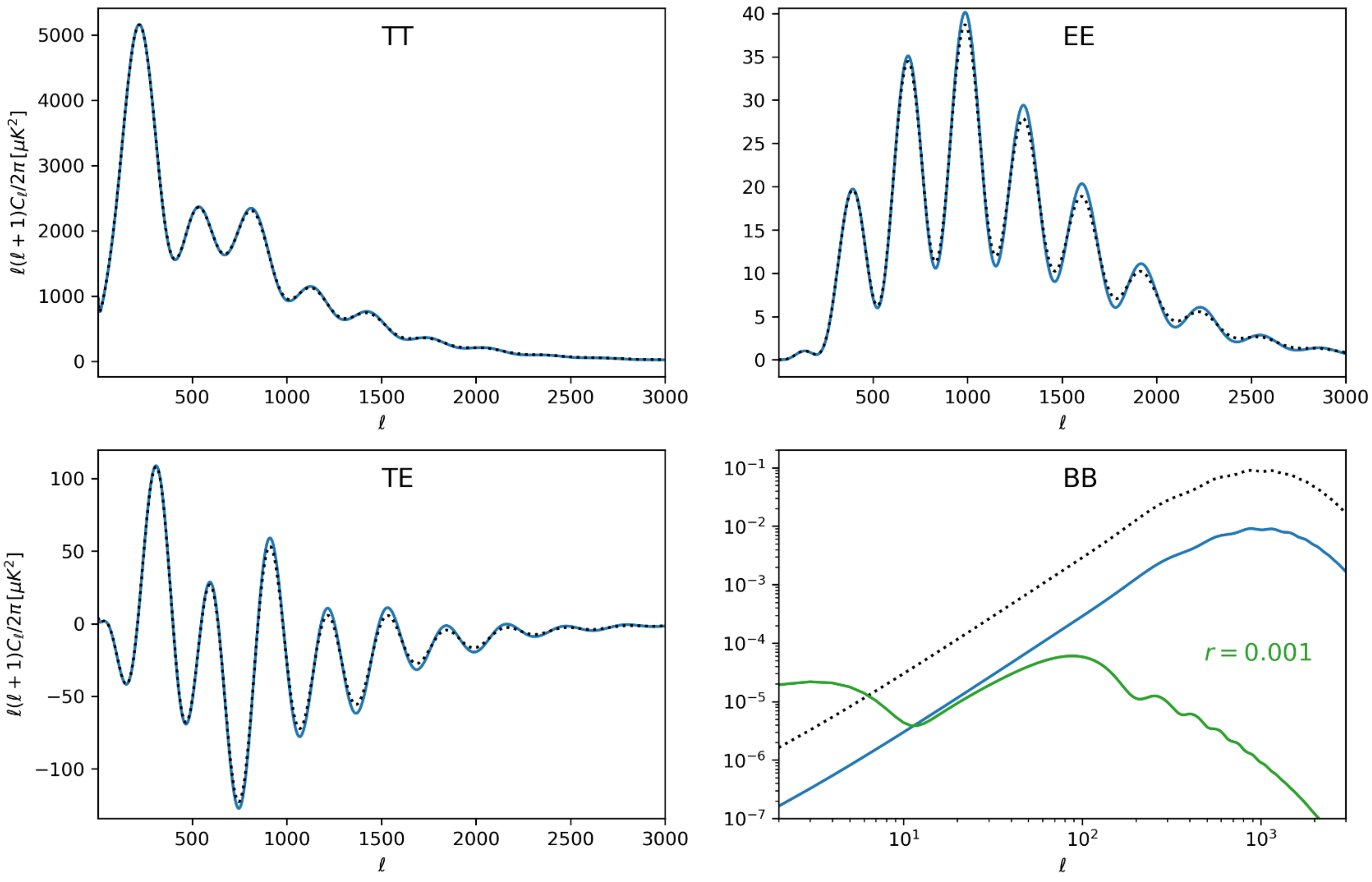
Delensing ($A_L = 1$)



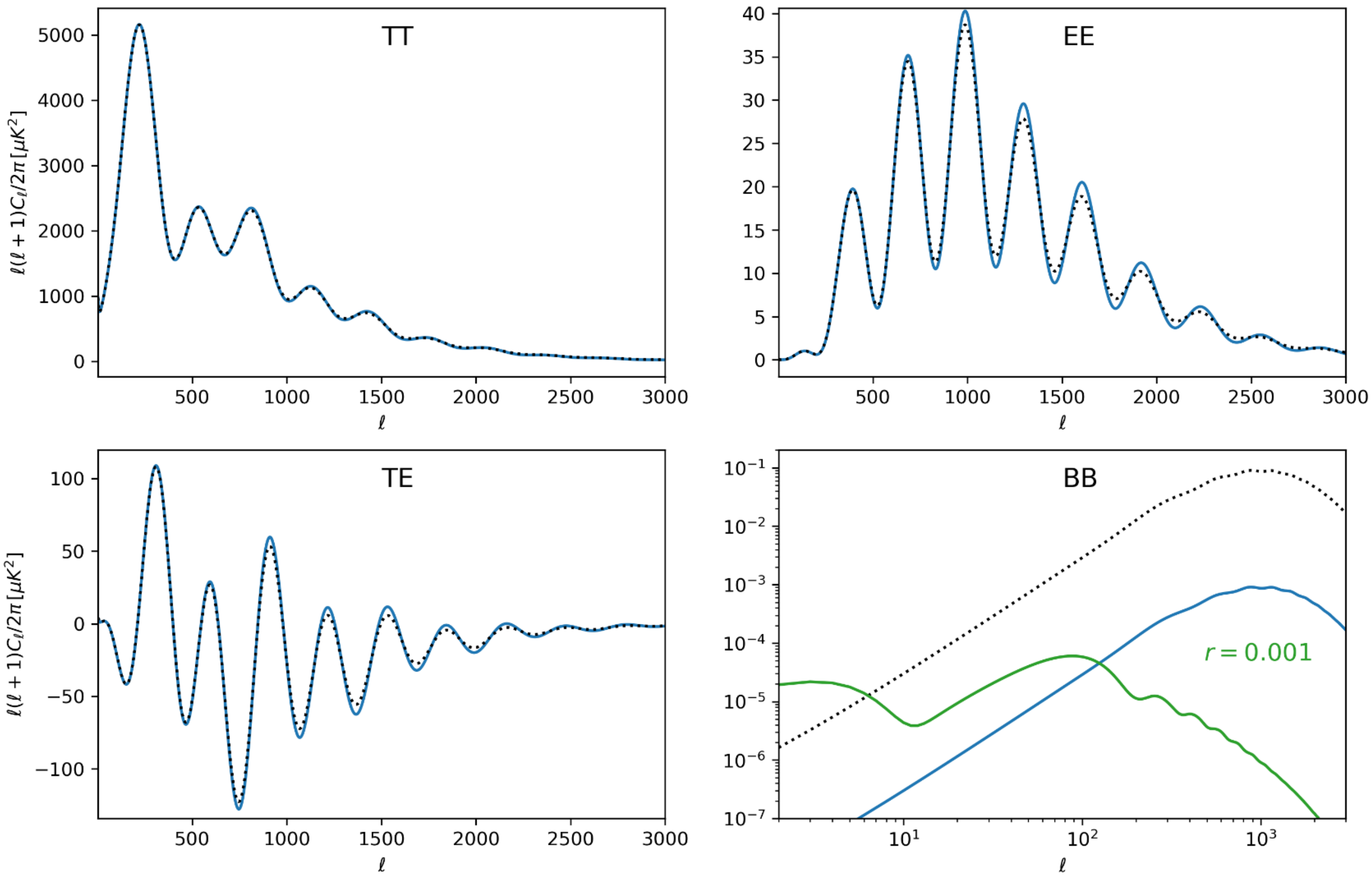
Delensing ($A_L = 0.5$)



Delensing ($A_L = 0.1$)

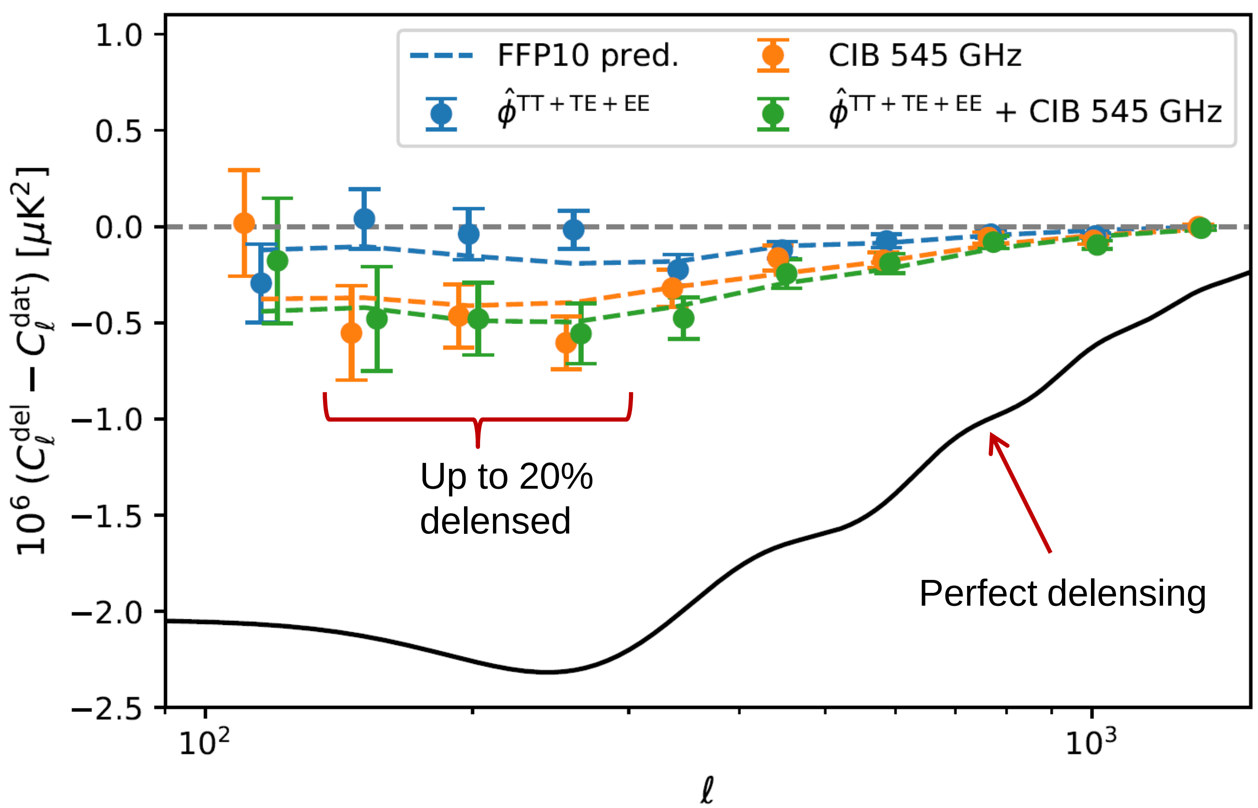


Delensing ($A_L = 0.01$)



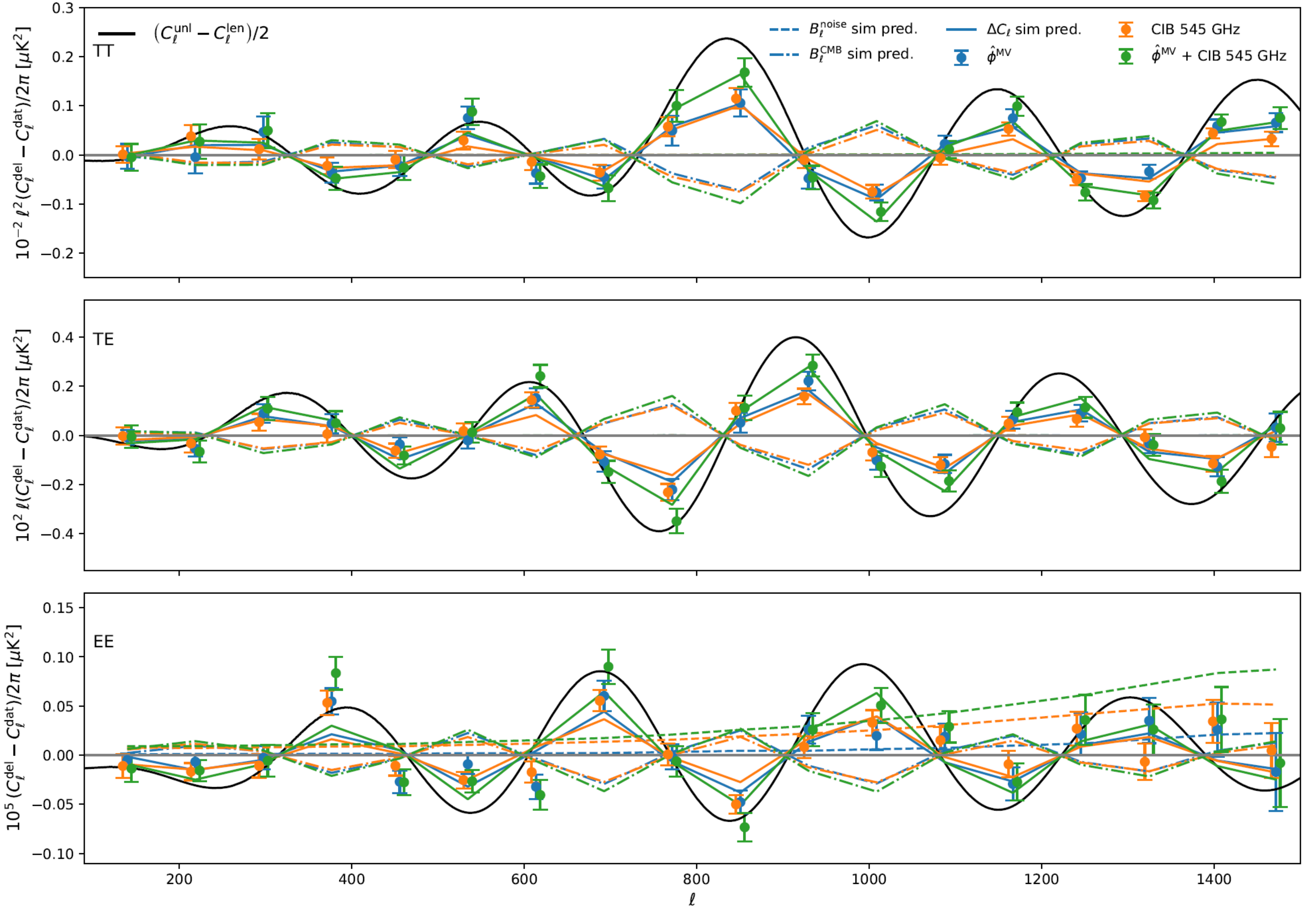
Planck B-mode delensing proof of principle

(limited delensing efficiency from Planck due to E noise)



Delensing: Peak Sharpening – 40% of smoothing effect removed with MV+CIB

$$\Delta\hat{C}_{\ell,\mathrm{debias}} \equiv \hat{C}_\ell^{\mathrm{del}} - \hat{C}_\ell^{\mathrm{dat}} - B_\ell^{\mathrm{Gauss}} - B_\ell^{\mathrm{Noise}} + B_\ell^{\mathrm{CMB}}$$



How well can we delens in principle?

Standard lensing remapping approximation:

$$\tilde{P}_{ab}(\hat{\boldsymbol{n}}) = P_{ab}(\hat{\boldsymbol{n}} + \boldsymbol{\nabla}\phi)$$

Observed		Theory	
$\tilde{E}, \tilde{B}$	lensing ← → Delensing?	E, ϕ	(almost all modes small-scale, unlensed $B = 0$)
2 d.o.f.		2 d.o.f.	

Perfect lensing reconstruction, hence delensing(?), if only 2 d.o.f.

Hirata & Seljak 2003

Can we construct an “optimal” lensing reconstruction algorithm?

YES, in sense of maximum a posteriori estimators:

- Hirata & Seljak 2003: iterative estimator for idealized full-sky (astro-ph/0306354)
  (with some approximations)

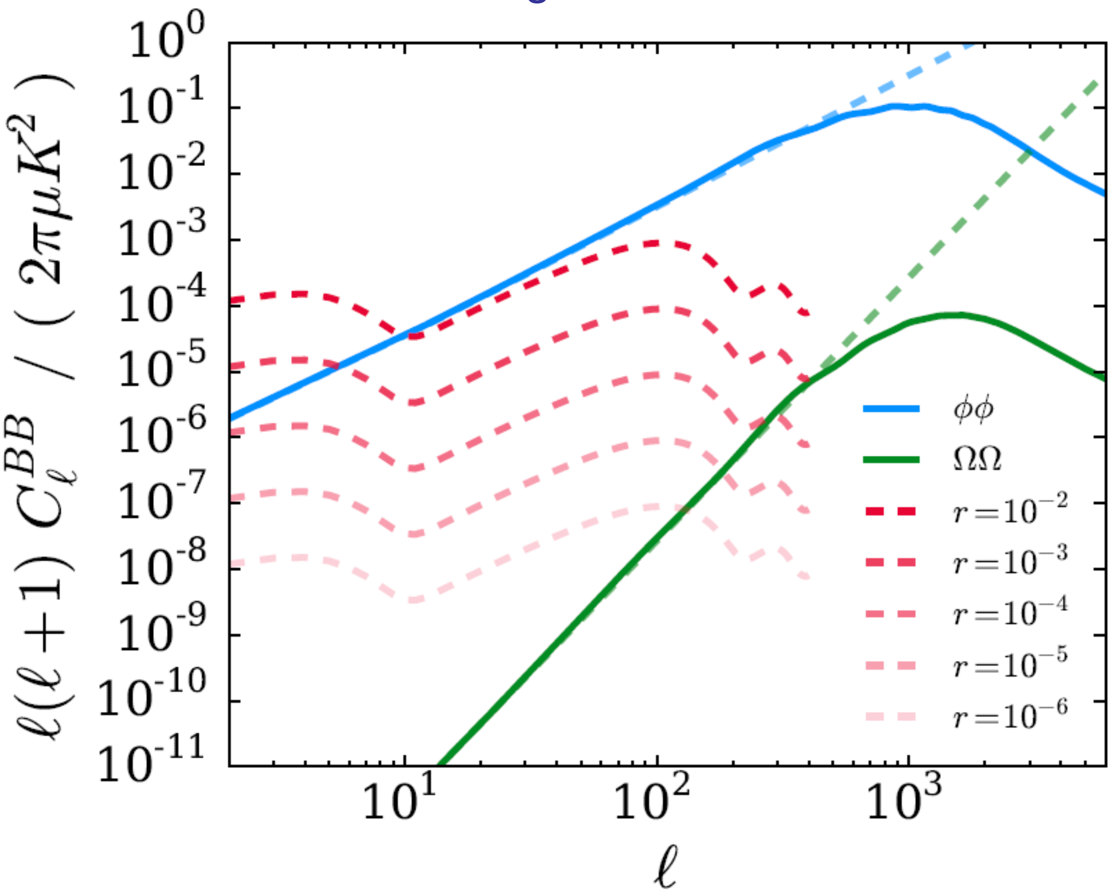
- Carron & Lewis 2017: public code that can be used in practice (1704.08230)
  (efficient handling of anisotropic noise, beams, sky cuts..)

LensIt:
https://github.com/carronj/LensIt (Julien Carron)

What limits delensing in principle?

1. Deflection not pure gradient:
   additional degree of freedom from post-Born field rotation/curl shear

B-mode signal from field rotation



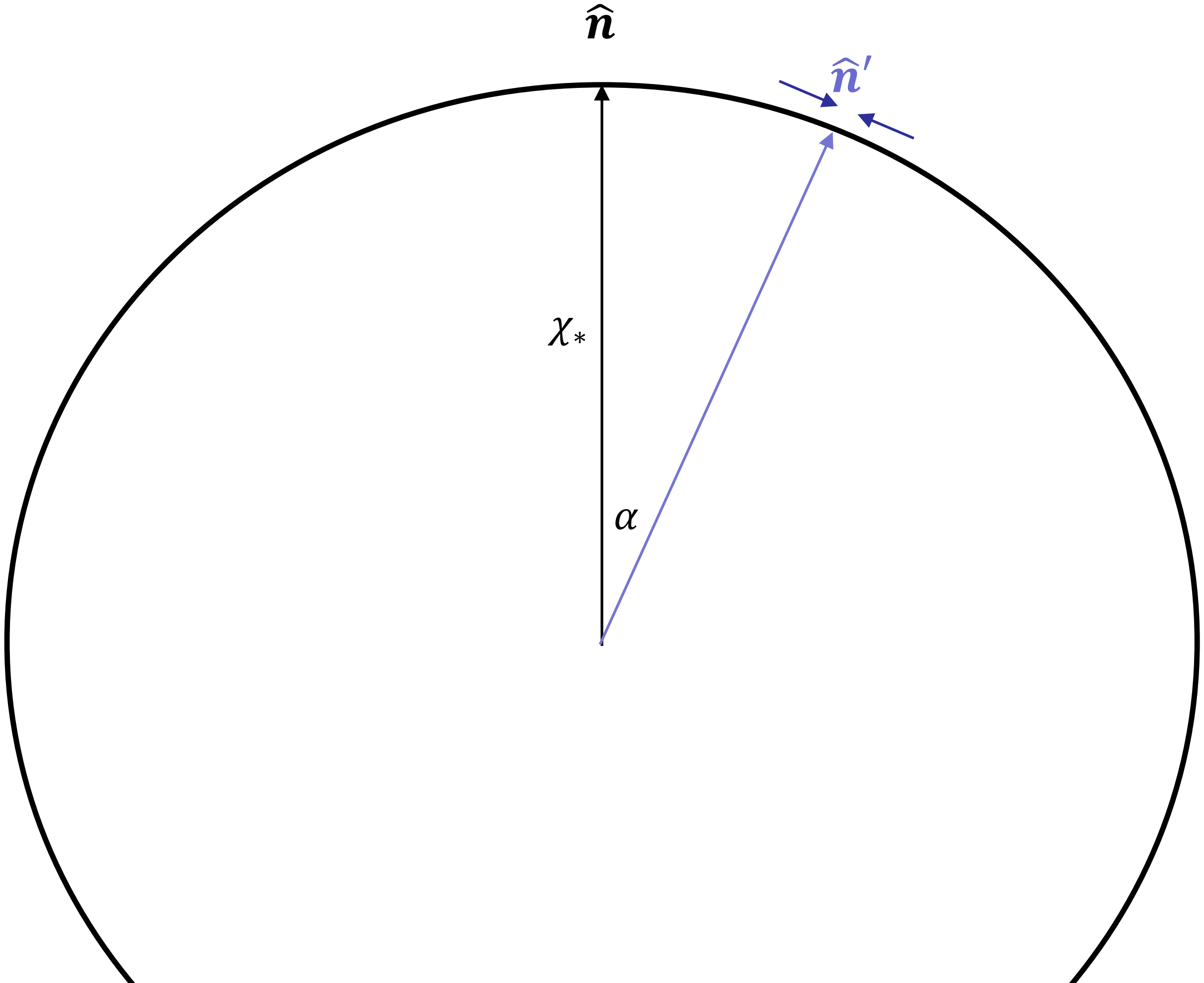
~2.5% of B mode amplitude from rotation
(effect of post-Born polarization rotation is negligible)

Pratten & Lewis: arXiv:1605.05662

2. Differences between unlensed and lensed last scattering

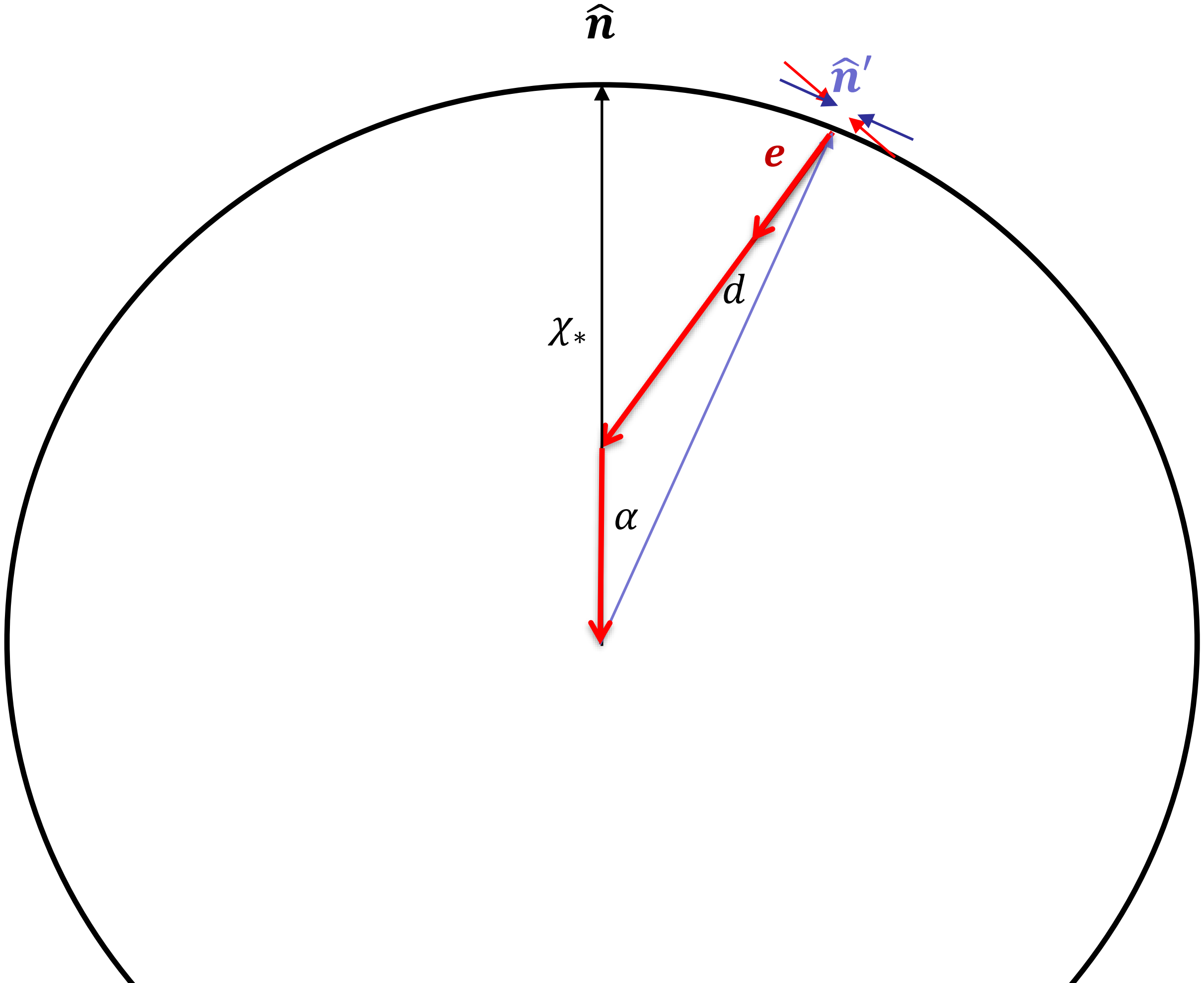
$$X^{\mathrm{len}}(\boldsymbol{n}) = X^{\mathrm{unl}}(\boldsymbol{n} + \boldsymbol{\alpha}(\boldsymbol{n}))$$

Lensed quadrupole: remapping approximation



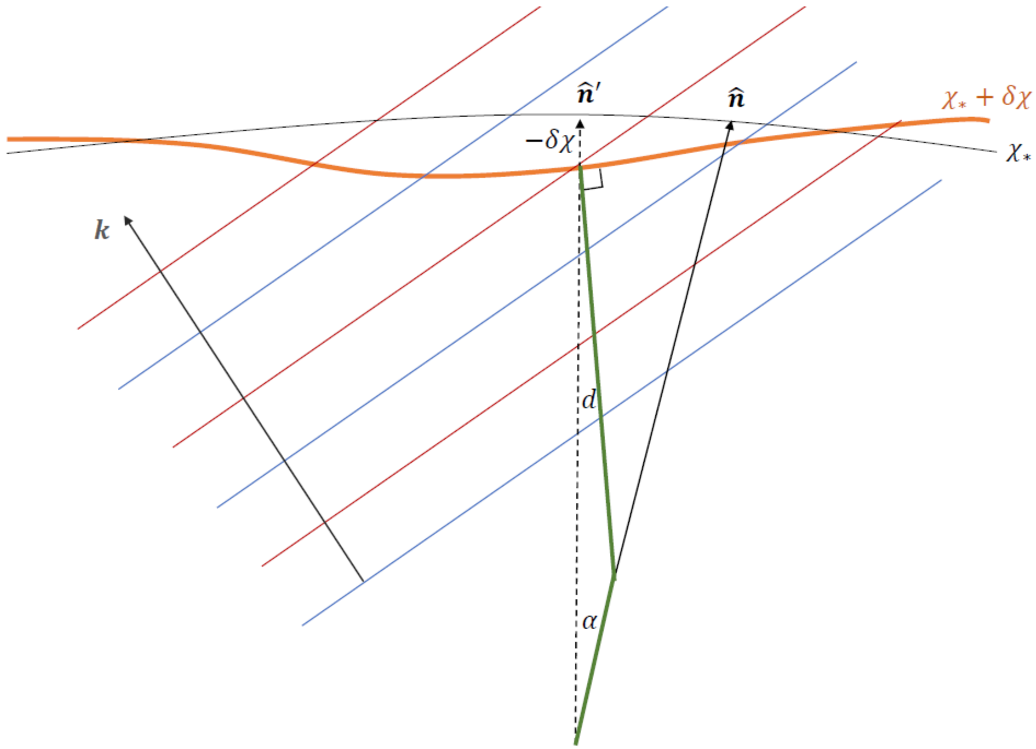
2. Differences between unlensed and lensed last scattering

Lensed quadrupole: with emission angle d
not the same as the unlensed CMB quadrupole: observe new modes



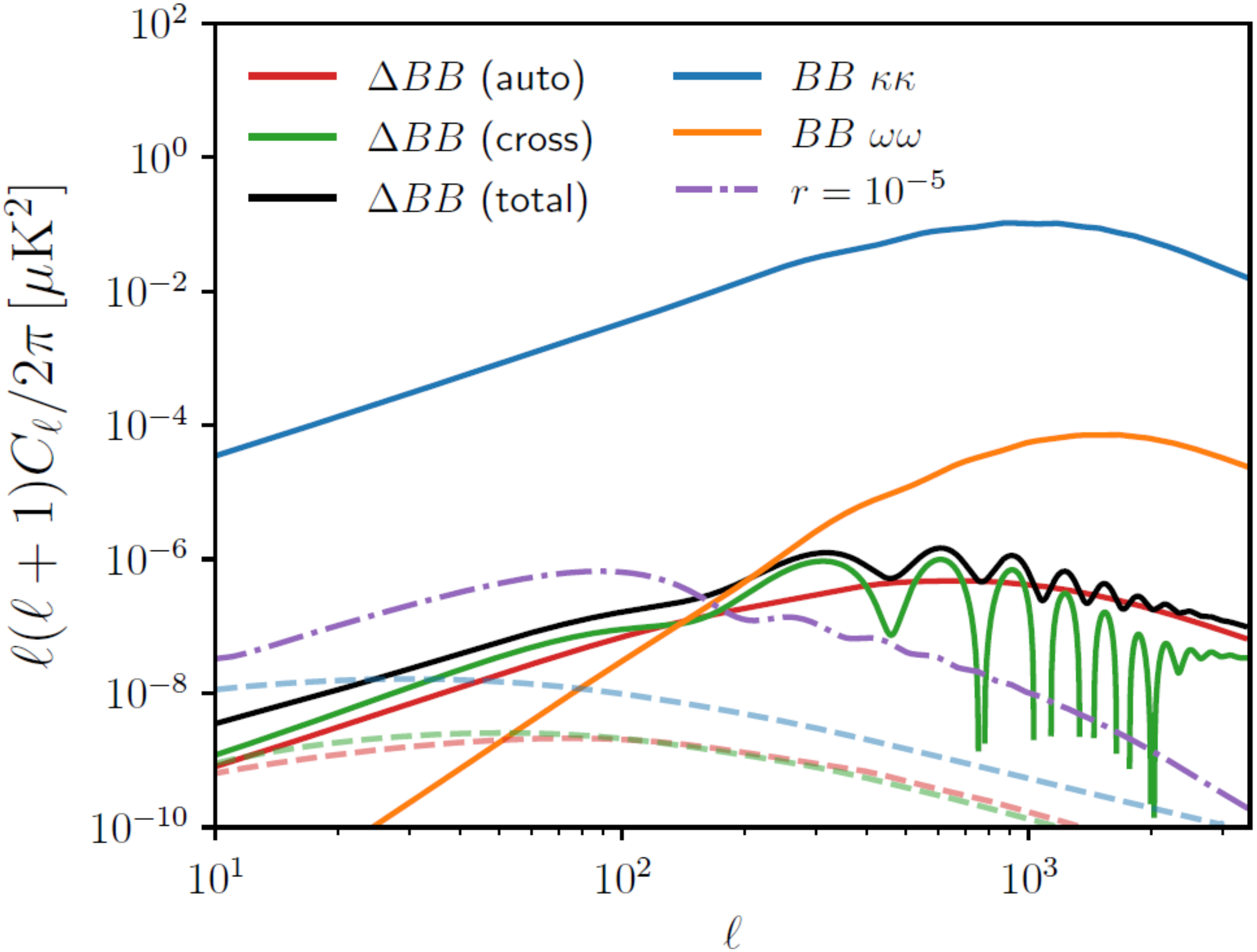
Fermat's principle: perturbed emission angle orthogonal to perturbed last scattering surface

Must also account for time delay perturbing last scattering



Total emission+time delay effect dominates on large scales

Lewis, Hall, Challinor arXiv:1706.02673



Emission angle+time delay: $\Delta r \sim 2 \times 10^{-6}$

Conclusions

- CMB lensing starting to be a powerful cosmological probe
  - high significance measurement with Planck
  - complementary to galaxy lensing

- Delensing works! Planck 2018 internal delensing:
  - High significance detection of peak sharpening (T/E)
  - First detection of B-mode delensing
  - Improved delensing using Planck CIB

- Low noise → can delens nearly perfectly (Hirata and Seljak)

- Optimal and practical iterative method for lensing reconstruction now exists (LensIt code).

- In principle limit? Emission angle+time delay: $\Delta r \sim 2 \times 10^{-6}$
  - Reionization signal larger, but no problem for foreseeable future
  (potentially much larger problems in practice - foregrounds etc)